VIBRATION EFFECTS ON
THERMAL CONTACT RESISTANCE

by

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ABSTRACT

This work is intended to be a preliminary experimental investigation of some vibration effects on thermal contact resistance. A FORTRAN II-D program has been written to compute the temperature drop across the metallic contact by extrapolating the temperature profiles in the two specimens towards the contact by using the least square approximation. Graphs plotted from the results indicate the general trends of vibrational amplitude, frequency and duration effects on the thermal contact conductance. It can be concluded that in the absence of excessive vibration, both in amplitude and duration, the vibration effect is of second order in comparsion with the effects due to the surface roughness and the applied normal stress. In the future, it would be interesting to investigate the vertical vibration or the fluctuating normal stress effects on thermal contact conductance so that a comparison between vertical and horizontal vibration effects can be made.

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NOMENCLATURE

Symbol	Description	Units
T_o	Mean contact temperature	^oF
h	Thermal contact conductance	$\frac{BTU}{Hr\text{-}Ft^2\text{-}^oF}$
r	Thermal contact resistance	1/h
k	Thermal conductivity	$\frac{BTU}{Hr\text{-}Ft\text{-}^oF}$
Amp	Vibration displacement	mils
f	Vibration frequency	1/sec
τ	Vibration duration	min.
P	Applied pressure	psi
σ	Arithmetic average roughness	μin.
w	Angular frequency	rad/sec.
CRT	Cathode-Ray Tube	
VG	Vibration generator	
I	Current	
V	Voltage	
AA	Arithmetic average	
rms	Root mean square	

CHAPTER 1

INTRODUCTION

In the field of nuclear reactor technology, especially the propulsion reactor, due to the enormous power density of the fission fuel, very high temperature gradient must be established from the fuel elements to their metallic clad. The temperature drop across metallic interface generated by the so called "thermal contact resistance" becomes significant. Also in aerospace research, lightweight materials often leads to poor thermal contact which cannot always be improved by high conductivity filler because of its fast evaporation rate. In recent years, several series of experimental studies on thermal contact conductance have been carried out both at MIT and at other engineering research centers in the world, in an effort to discover important parameters of the phenomenon, to predict its magnitude correctly and to formulate methods of reducing its undesirable effects.

To date both experimental and theoretical research in this area have proceeded on the assumption that the metallic contact is mechanically static with respect to its immediate surroundings. In reality, most engineering applications involving metallic contact heat transfer problems are inherently subject to mechanical vibrations of one form or the other.

The basis of this report is a preliminary experimental investigation of vibration effects on thermal contact resistance. The accuracy of the results is very debatable because of the large uncertainty of vibration detection instrument and the suitability of characterizing the vibration by its displacement amplitude and its fundamental frequency only.

The results of the experiment was computed by a IBM 1620 Data Processor. The program was written in FORTRAN II-D . With a slight change it could be complied by IBM 7094 of Computation Center at MIT. The function of the program is to calculate the thermal contact conductance, its equivalent thickness and also its dimensionless parameters for correlation of various variables that have significant influences on the overall behavior of this phenomenon.

In this work, Chapter 2 and Chapter 3 give a brief description of temperature and vibration measurement techniques and their associated instruments used in this experiment. Chapter 4 deals with a method of preparing and characterizing a finished surface (glass-bead blasting). A simplified dimensional analysis of this problem is described in Chapter 5. The following three chapters are the core of this report. They are concerned with test apparatus, the experimental procedures and the experimental results. The last chapter is the conclusion. A brief recommandation for future research is this area is included in the conclusion.

CHAPTER 2

VIBRATION GENERATION AND DETECTION

A body is said to vibrate when it executes an oscillatory motion about a position of equilibrium state. In the study of forced vibration, there are two main types of forcing actions, the impulsive and the harmonic. Their effects on the system are quite different.

In the impulsive perodic vibration a mass receives impulses or blows at constant intervals, causing it to deflect. After a blow has been received the mass will vibrate at its natural frequency. The amplitude will gradually decrease with time due to damping. If the blows are repeated at regular intervals the amplitude may be large or small depending upon the ratio of the forcing frequency to the natural frequency.

The second type of periodic force is the harmonic, which is very common in vibration work. It may be expressed mathematically as $F = Fo * Cos(wt)$, where Fo is the maximum amplitude and w is the frequency in radians per second. The Goodmans V-50 Vibrator gives an output of this type as shown in Plates 4 & 5.

2.1 Vibration Theory

Theoretically, any periodic vibration consists of a number of simple harmonic motions with frequencies which are integral multiples of a fundamental frequency. Mathematically, this is a direct result of Fourier's Expansion Theorem. Experimentally, this phenomenon can be easily verified by Wave Analyzer (e.g. General Radio's meter-type wave analyzer and Tektronix's CRT oscilloscope type wave analyzer).

Since the equation of motion for a spring-mass system is linear, solution for individual harmonics can be superimposed directly to produce a solution for the sum of the harmonics. However, the vectors which represent the solutions for the various harmonics are not necessarilly in phase with the force that produced them. The solution must be a vector sum, and although this complicates the process of obtaining complete solution, it is nevertheless quite simple to make some generalizations.

For a system with small damping, the response to a harmonics near natural frequency of the system will be large

It should be remembered that the magnification factor represents the ratio of dynamic response to static response for the same force. In most cases the harmonics beyond the first few, drop in amplitude rapidly, therefore, even though the magnification factor may be large for one of these high harmonics, its absolute magnitude is negligible and has little effect on overall system response.

2.2 Vibration Generator

The Goodmans V-50 Vibrator is an electro-mechanical transducer that changes electrical current to mechanical force. This effect is caused by a coil suitably oriented in the field of a permanent magnet (Fig.1) an alternating current being passed through it. However, electro-mechanical effects can be obtained electro-statically (e.g. the condenser loudspeaker), and also with piezoelectricity and magnetostriction. Such devices are extremely useful since they enable mechanical systems to be linked to electrical and electronic devices to produce or detect vibrations.

Equation of motion of this moving coil transducer is

$$m\frac{d^2x}{dt^2} + sx - Bli = 0 \tag{2-1}$$

where sx is an elastic restraining force,
Bli is the magnetic force.

For sinusoidal current, i is porportional to Sin(wt). The steady-state solution of the above differential equation is $X_{ss} = \dfrac{\sin \omega t}{S + (-\omega^2)}$. Thus if the input current is made sufficiently close to sinusoidal form, then the output vibrational displacement of the transducer will also be in the form of sinusoidal as far as steady state is concerned.

The mechanical force and electrical current are related by

$$F = 0.885(10^{-7}) * BLI \qquad (2\text{-}2)$$

where F = force in pounds
B = magnetic flux density in lines/in
L = length of current carrying conductor (inches)
I = current in amperes

When this vibrator is applied to test specimens, we have essentially a forced vibration of a damped single degree of freedom system.

The force balance gives

$$M\frac{d^2Y}{dt^2} = -k - c\frac{dY}{dt} + F \qquad (2\text{-}3)$$

Assuming sinusoidal forcing function

$$F = Fo * \exp(jwt) \qquad (2\text{-}4)$$

$$M\frac{d^2Y}{dt^2} + c\frac{dY}{dt} + k = Fo * \exp(jwt) \qquad (2\text{-}5)$$

Dividing by M and let $w = \sqrt{\frac{k}{M}}$, and $\zeta = \dfrac{c}{2\sqrt{M/c}}$

then yields a characteristic equation

$$\frac{d^2Y}{dt^2} + 2\zeta\omega_n\frac{dY}{dt} + \omega_n^2 Y = \frac{F_c}{M}\exp(-j\omega t) \qquad (2\text{-}6)$$

Steady state solution for this differential equation is

$$Y_{ss} = \frac{F_0}{k\left[\left(1-\frac{\omega^2}{\omega_n^2}\right)+j2\zeta\frac{\omega}{\omega_n}\right]}\exp(j\omega t) \qquad (2\text{-}7)$$

With a phase angle of $\phi = \mathrm{Tan}\,\dfrac{-2\zeta\omega_n\omega}{\omega_n^2-\omega^2}$

This stady state solution is just a part of the total solution which includes also the complementary solution. Plate 5 gives one illustration of this solution.

Note $\dfrac{1}{1-\frac{\omega^2}{\omega_n^2}+j2\zeta\frac{\omega}{\omega_n}}$ is the magnification factor.

The major components of the vibrator comprising the yoke, magnet and pole tip, moving coil assembly, centring plate and top cover. The magnetic circuit is formed by the slug magnet, the pole tip, the yoke and the front plate and producess a magnetic field which is concentrated in the annular air-gap.

As mentioned above, the vibration generator functions by virtue of the interaction between the magnetic field and an oscillating current flowing in the coil of the moving assembly. The driving current is derived from a power amplifier coupled with an audio oscillator. The amplitude of displacement at the moving coil is controlled by the power gain of the amplifier. The frequency of vibration is preset by the oscillator. A test load mounted on the armature driving spindle can, therefore, be vibrated at any frequency fixed by the oscillator and at any amplitude within the performance envelope of the machine. The operating procedure for this vibrator is relatively simple, but it is imperative to take certain elementary precautions specified in the manual, to avoid overloading the vibrator electrically and mechanically. These are: (1) always use the auxiliary suspension to support the spindle, (2) apply air cooling whenever possible, (3) never exceed the maximum allowable current or voltage rating of the vibrator.

2.3 Vibration Detection

A large variety of mechanical, optical and electrical instruments have been developed to measure frequencies, displacements, velocities and accelerations of both rectilinear and torsional vibrations. In this experiment, the General Radio's Type 1553-A Vibration Meter is employed. It is a portable, general-purpose electronic instrument for measuring vibration. From the standpoint of precision, it is a rather crude instrument, because the uncertainty of its reading is usually more than ten percent.

The Vibration Meter consists of a piezoelectric ceramic accelerometer-type pickup and a sensitive vacuum tube voltmeter. The principle of its operation is that when the crystal inside the pickup is stressed, proportional to this external stress, measurable electric charges are set up on certain crystal faces. By fixing two adjacent sides of the crystal, inertia forces will be created that are proportional to the acceleration. The induced voltage may then be amplified to yield the acceleration of the crystal. The corresponding velocity and displacement can be obtained by integrating electronically once and twice respectively of the original signal. The basic integrating circuit is shown in Fig. (3). The output meter circuits consist of zero to peak, peak to peak and average circuits. They are essentially rectifier circuits making use of the switching properties of semiconductor diodes.

The procedure of operation is simple but reliable reading is quite difficult to get. This is primarily due to the extreme sensitivity of the vacuum-tube voltmeter cicuit. One possible way of by-passing this undesirable effect is to feed the output of the vibration meter to a cathode-ray-tube oscilloscope. The block diagram for this setup is shown in Fig. (2).

CHAPTER 3

TEMPERATURE MEASUREMENT

The thermocouple, or thermoelectric thermometer is probably the most widely-used temperature measuring instruments. It has been applied over the entire range from the immediate vicinity of absolute zero to 5400 °F, whereas in range from 1167 °F to 1945 °F it is specified in the International Temperature Scale as the most precise and reliable of all temperature indicating devices. The temperature-sensitive element in a thermocouple can be made arbitrary small, thus facilitating precise measurement of temperature at a point. The smallest thermocouple wire available in industry is only one mil in diameter which is about ten to fifteen times smaller than the 28 and 30 gage wire now commonly used in most laboratories. The low thermal capacity of the element, resulting from this small size, tends towards quick response and facilitates measurement of temperature instantly.

The thermocouple itself is very cheap and simple in construction. The indicating instruments are usually quite elaborate. They, however, can be locate at a distance from the body and used for reading a large number of thermocouple alternately. Because of its remarkable combination of characteristic, the thermocouple is considered to be best suited for application in measurement of internal temperature in solids.

3.1 Thermocouple Circuits

The thermocouple technique is the most widely used method of measuring internal temperatures in solid bodies. However, certain precautions must be followed in order to obtain results of high (±0.5 °F) degree of precision.

A thermocouple circuit may contain four metals. This is the case when the leads are, for practical reasons, made of materials different from those used for the thermocouple proper. In practice, thermoelectric circuit always include indicating instruments, switches,etc. The portion of the circuit through any such device always consists of several metals. If the temperature throughout any such switch or indicating device is uniform, no error will result. Likewise, the smaller the variations in thermoelectric properties among the various metals used, the smaller the resulting error will be for a given degree of non-uniformity in temperature within the group of switches and indicating devices. The metals for this portion of the circuit are customarily limited to copper, brass, lead-tin solder, silver and manganin, since the thermoel ctric properties of these metals do not differ greatly i.e. they have low thermoelectric powers with respect to one another. A correction for this effect can be estimated by noting the reading when the thermocouple is shorted out.

Throughout this experiment, the 28 gage Chromel Alumel thermocouples are used for sensing the internal temperature of the specimens. The reasons for this selection are because of its ability to sustain high temperature and its ruggedness. Since most indicating instruments have lead wires made of copper, special wiring technique is required to eliminate the additional emf generated at various connections. This is shown in Fig. (4).

Theoretically, each thermocouple needs two cold junctions and its output goes to a selector switch which is connected to a potentiometer or a recorder. If this is the case, four to five thermo-bottles are needed for housing about thirty cold junctions. Obviously, the maintainance will creat inconvenience. A compromise is made at this point. A high quality thermocouple switch is connected between hot and cold junction as shown in Fig. (5). In this manner, only one cold bath is enough for entire operation.

This is, of course, achieved at the expense of slight experimental error . However, in future experiment, if financially feasible, it will be much better off for the experimenter to use the electrical reference junction which is compact, accurate and maintainance-free.

3.2 Indicating Instruments

Temperature measurements are divided into two stages. The first stage is for preliminary balancing of the temperature profiles in specimens and guard ring. Brown Potentiometer Recorder is used for this purpose. The second stage is for final balancing and data-taking. At this stage, Leeds & Northup 7553-6 Type K-3 Universal Potentiometer is used. Since it is both electrically shielded and guarded by special circuitry, it is capable for highly accurate measurement of dc emf. For the temperature of interest, the measurement uncertainty can be narrowed down to two microvolts which corresponds to about 0.1 F for Chromel-Alumel thermocouple. The accessory components are the L&N 7308 Eppley unsaturated Standard Cell; 099034 Constant Voltage Supply; L&N 9834 Electronic DC Null Detector. The operation of the entire system is quite simple. Much of it are very similar to the operation of ordinary potentiometer. The circuit connection and operation procedures are in the instruction manual.

CHAPTER 4

SURFACE PREPARATION

The pattern of the machine-finished surfaces are formed by repetitive or random deviations from the norminal surface. In general, surface texture includes roughness, waviness, lay and flaws.

4.1 Roughness Characterization

According to the American Standards Association, *Arithmetical Average deviation from center line is

$$Y_{AA} = \frac{1}{\ell} \int_{X=0}^{X=\ell} |Y| \, dX \qquad (4\text{-}1)$$

where l = length over which the average is taken
y = ordinate of the curve of profile

Graphically or approximately, arithmetical average can be obtained from surface profile graph by sampling at regular interval. The average of the magnitude of the ordinate is the approximate A.A. value of the surface. i.e. $Y_{AA} = \frac{|Y_1| + \cdots |Y_N|}{N}$

Incidentally, the center-line average (CLA) used in Britain has essentially the same definition as arithmetic average.

*Many instruments now in use employ an average squared-deviation from the center line as

$$Y_{rms} = \frac{\left[\int_{x=0}^{x=\ell} y^2 dx\right]^{1/2}}{\ell^{1/2}} \qquad (4-2)$$

This type of average is known as root mean square and is commonly used in the electrical industry. Roughness measuring instruments calibrated for root mean square average will be found to read approximately 11% higher on a given surface than those calibrated for arithmetic average.

This difference, however, is of lesser magnitude than the variation from point to point on a machined surface and is considerably less than the variation expected from one piece to another. The quantity which has been found most useful in characterizing a surface is the average roughness height.

4.2 Surface Lapping

All specimens come out of machine-saw have to be smoothened first before they can be lapped. This is merely a precaution against damaging the lapping machine, the Lapmaster. (Plate 3.1)

Lapping is a time-consuming process. Even for the well-smoothened surface, it usually takes about an hour to approach the maximum degree of flatness. The work as it comes off the Lapmaster can be tested for flatness with Monochromatic Light and Optical Flat. Testing for flatness is done by reflecting the light emitted from the Monochromatic Light head, and from the surface to be checked through the Optical Flat. Thus a series of dark bands and light spaces are observed. It is the result of interference produced by reflections from the test piece and the Optical Flat. If the bands are curved the surface is not flat enough. These bands are part of the much larger circles of the so called "Newton rings". Therefore, for perfect flatness, there would be no bands.

To determine flatness under Monochromatic Light whether the surface is convex or concave, move your eyes away gradually from the optical flat along the line of vision. The light bands will flow either towards or away from center of the circle. Visualize the light bands as a portion of a large circle, the center of which is off in the distance. As you move your eyes away from the optical flat along the line of vision, if the bands appear to go in towards the center, the surface is low toward the center and the lap plate is high in the center and vice versa. Light band reading through an optical flat using a monochromatic light source, represent the most accurate method of checking surface flatness.

The monochromatic light comes from helium-filled tube source which eliminates all colors except a yollowish orange. Wavelength of light from this source is $23.2(10^{-6})$ inch. However, since only one half of the wavelength is used, the increment of measure is $11.6(10^{-6})$ inch.

The dark bands viewed beneath the optical flat are not light wave. They simply show where interference is produced by reflections from two surfaces. The dark bands is used in measuring flatness. The band unit is $11.6(10^{-6})$ inch; that is, between the center of one dark band and the center of next dark band, the level of the surface has changed by $11.6(10^{-6})$ inch in relation to the optical flat.

4.3 Surface Finishing

Since there is no facility for making roughness on metallic surface at MIT, the lapped specimens have to be sent out to Potters Brothers, Inc., Carlstadt, New Jersey for glass beads blasting. The roughness of the finished surface depends on the blast pressure and glass bead size. Table 1 gives some idea on how these two specifications would affect roughness of the finished surface.

The detailed description of the glass-bead blasting is not known; however, it is very likely that in the process of making roughness the original flat surface is distorted to some extent. Since this undesirable effect is not directly controllable, some errors will eventually show up in the final results. In the future, part of this error can be corrected by taking a waviness measurement of the finished surfaces. Of course, the waviness will then be treated as an additional variable in the final analysis.

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*Extracted from Surface Texture (ASA B46.1-1962) with permission of the publisher, ASME, United Engineers Center, 345 E.47th St.,N.Y.C.

CHAPTER 5

DIMENSIONAL ANALYSIS

In problems of engineering and physics, people have always made use of dimensions in checking formulas. The idea of dimensional consistency can be used in another way, by a procedure known as dimensional analysis, to group the variables in a given physical phenomenon into dimensionless parameters which are less numerous than original variables. The immediate advantage of this procedure is that considerably less experimentation work is required to establish a relationship between the variables over a given range. Furthermore, the nature of the experiment will often be much simplified. However, a complete solution is not obtained nor is the inner mechanism of a phenomenon revealed by dimensional homogeneity.

Dimensional analysis has a serious limitation. That is, it gives no information about the nature of a phenomenon. In fact to apply dimensional analysis it is necessary to know beforehand those variables which have influences on the phenomenon, and the success or failure of the method depends on proper selection of these variables. It is therefore essential to have at least a preliminary theory or a thorough physical understanding of a phenomenon before a dimensional analysis can be performed.

5.1 Selection of Variables

The recent studies on thermal contact conductance have sorted out the pertinent variables and more important, discovered their relative influence on thermal contact conductance or resistance.

For the present case of vibration effects on thermal contact conductance, the first step is to select the variables which have significant influences on the thermal contact conductance. For the sake of simplicity, let us assume that the surface is flat. With some reservation, only seven variables will be used in the following analysis. These are: roughness (σ); pressure (p); contact temperature (T); vibration frequency (f), displacement (Amp), and duration (τ); and finally the thermal contact conductance (h).

5.2 Result by Buckingham Pi Theorem

Since there are seven variables and four basic dimensions, it is expected that three dimensionless parameters are needed to characterize the phenomenon. Straightforward algebraic manipulation yields

$$\pi_1 = \frac{\sigma p f}{\tau_0 h} \qquad (5\text{-}1)$$

$$\pi_2 = Amp/\sigma \qquad (5\text{-}2)$$

$$\pi_3 = f\tau \qquad (5\text{-}3)$$

Hence the dimensional analysis has enabled us to relate the original seven variables in terms of only three dimensionless parameters in the form

$$\frac{\sigma p f}{\tau_0 h} = \phi\left(\frac{Amp}{\sigma}, f\tau\right) \qquad (5\text{-}4)$$

This is the direct result of the application of Buckingham Pi Theorem which gives no physical meaning to the resulting dimensionless parameters. The validity of this result is greatly dependent upon the assumptions made before its derivation. It is hoped that the experimental result will be able to throw some light on the above dimensional analysis.

CHAPTER 6

TEST APPARATUS

Photographic views of the experiment setup are shown in Plate 1 & Plate 2. The test apparatus consists mainly of a dead-weight press, a coil heater placed on top of test specimens and a water cooler directly below it.

The press has two multiplication arms mounted on a rigid base. Three different combinations of these lever arms give three force multiplication factors. These are approximately 3.0, 20.0 and 45.0. Their exact values have to be measured for each setup. This press theoretically can provide compressive force ranging from 70 lb to 22,500 lb. For a 1" diameter specimen, the corresponding pressure range is 95 psi to about 29,000 psi.

The compressive force applied on the test specimens is transmitted through a 3/4" diameter steel ball so that the compressive stress in contact junction is uniform across the plane of contact.

The heat source is the electrical heating of resistance coil. It has a capacity of about 1 kilowatt, however, the maximum output is restricted by the melting point of the ceramic insulation which is about 2000 °F. The inner structure of the heater is shown in Fig.(7). This heating coil is insulated by a 1" thick cylindrical refractory brick which is further wrapped by asbestos sheet and aircraft fibre glass insulation. Power supply to this heater is regulated by a 2.4 kva Powerstat(Variac). The power input to the Powerstat is the 115 volts, 60 cps AC line. Since no provision is made to eliminate the slight variation of the line voltage, it is difficult to attain desirable degree of temperature equilibrium in the test specimens.

The heat sink (Fig.13) is the forced convection water cooler. It is essentially a stainless steel cylindrical container with a finned copper core. The cooling rate is regulated by the water flow rate. Again, the water temperature and its pressure are not controlled by any devices, hence the unavoidable slight fluctuation will definitely contribute errors as the result of the nonsteady-state temperature profile measurement.

Despite of the above-mentioned shortcomings, every effort has been made to cut down heat loss as well as to obtain a maximum degree of equilibrium. One of such measures taken is to install a guard ring arownd the test specimens. It has its oun heating coil at the top and a ring cooler at bottom. This stainless steel guard ring is 1/16" thick and 4" in diameter. By regulating both the electrical power input and water flow rate, it is therefore possible to match satisfactorily the temperature profiles in guard ring with that of the test specimens.

The wattage, voltage and amperage are monitored by means of a meter panel which houses two wattameters, two ammeters, one voltmeter and a 16-position rotary switch.

In order to maintain linear temperature distribution in the guard ring so that it will effectively cut down radial heat transfer along the specimens, air-craft fibre glass is used to wrap the outside surface of the guard ring. Futhermore, the annular space between the test specimens and guard ring is filled with Pyrex glass wool to prevent natural convection and to reduce radial conduction heat transfer.

The test specimens are one inch in diameter and one and a half inch long. The contact is obtained by pressing end to end of two specimens. The contact surface is specially prepared. It was lapped to minimize its waviness first and then sent to Potters Bro. Inc., Carlstadt, New Jersey for glass bead blasting.

CHAPTER 7

EXPERIMENTAL PROCEDURES

Before carrying out the experiment, the first thing is to check out that all the monitoring meters and thermocouple switch are connected properly and also that the thermo-bottle is filled with ice-water mixture to the proper level. Secondly, all thermocouples has to be checked to eliminate the possibility of any bad welding which could very well give erroneous reading. Thirdly, the applied pressure is to be preset by hanging measured dead weight at the end of the lever arm which is supported by a hydraulic jack.

The next step is to insert each thermocouple into the holes in the specimens. It is preferable to use some high conductivity lubricant e.g. Silver Goop to insure good thermal contact between the specimens and the thermocouples. These thermocouples could be secured in place by glass cloth tape. The final step is to put specimens in position, align properly, release the hydraulic jack and cover the specimens with insultions, including the guard ring.

Several adjustment of the power supply has to be made at the beginning in order to obtain a contact temperature in the neighborhood of 150 °F. Once this is done, the follow-up is most difficult and to some extent crucial in the entire experiment. It is to match the guard ring temperature profile with that of the specimen. Due to the temperature drop across contact, it is desired to have guard ring temperature profile closedly resemble the one shown in Fig.(10). In other words, the temperature at top of guard ring should be one or two degrees lower than the corresponding temperature on the surface of top specimen and one or two degrees higher at bottom. The difficulty comes mainly from the fact that absolutely no facility is provided to control the undesired slight fluctuating line voltage and water temperature and pressure. Also the crude control of flow rate and power supply futher aggrevates the situation.

Since each pair of specimens is to be tested thirty to forty times for different conditions, it is important to prevent the surface from being distorted at early stage. One way to achieve this is to test each specimen with low pressure and high frequency, then decrease the frequency stepwise before each increment of pressure. This is because of the large impedance mismatch at high freouency between the power amplifier and the vibrator, therefore, less vibration power can be applied to the contact surface. Consequently, less distortion of the contact surface is expected than if the tests were started from low frequency. It should be emphasized that all measurements were taken two to ten hours after the termination of vibration. This is of necessity for minimum thermal equilibrium.

For the test of vibration duration effect, both the frequency and amplitude were fixed. Measurement was taken after a varying period of vibration had been given to the contact. The period of vibration increased from zero to about ten minutes in varying length of step. Since vibration was assumed accumulative, in plotting, vibration duration was taken as the sum of all previous periods of vibration given to the contact up to that data point. For the test of vibration amplitude effect, only the amplitude was allowed to vary and the amplitude varied from small to large in three steps. As to the vibration frequency effect test, both the amplitude and duration were fixed. Due to operation difficulty (explained in next chapter), the frequency could be varied only in a rather narrow band (20 to 200 cps) at low end of the possible frequency spectrum (20 to 2000 cps). The tests were done from high frequency (200cps) down to the low end of 50 cps. The plotting procedure in the figures for these two tests was straightforward. The detail of the results were presented in the form of graphs. No attempt was made in this report to develope a theory to describe these resluts quantitatively.

CHAPTER 8

EXPERIMENTAL RESULTS

This experiment was officailly started in the middle of Febuary of 1966, but the first fifteen weeks were exclusively spent on design and construction of test apparatus and on purchasing of needed instruments. The first run of test did not take place until the early June.

The experiment was carried out in such a manner that in every run only one of four controlled variables is allowed to change. These variables are the surface roughness, the applied pressure, the vibration frequency and the vibration amplitude. The surface waviness is assumed zero because the surfaces are made as flat as possible. Obviously, some errors are introduced here by such simplifying assumption.

Three series of test was aimed at investigating the vibration duration effect on the thermal contact conductance. One of these was done using stainless steel 303 specimens of geometric mean roughness 39 microinches and applied pressure of 3055 psi. The other two tests were performed using Aluminum 2024-T4 specimens of geometric roughness 239 microinches for two different pressures of 287 psi and 3055 psi.

The majority of the tests were performed with fixed duration of vibration (5 minutes). Such process was carried out 148 times for four pairs of stainless steel specimen of geometric mean roughness 6.7; 38.7; 156.2; and 226.1 microinches. The pressure range tested was 287 psi to 6891 psi and the range of vibration frequency was from 50 cps to 1000 cps. As to vibrational displacement, its amplitude was proportional to power amplifier output but limited by the vibration generator's performance characteristic which was highly dependent on frequency. Roughly, the range was from 0.02 mil to about 2 mils at low frequency.

The data processing is quite time-consuming therefore a computer program was written. It was done in FORTRAN II-D language which was particularly suited to IBM 1620 Data Processor of Aeroelastic and Structures Research Laboratory at MIT. The major portion of the computer program was to extrapolate the data points in top and bottom specimens to the contact surface by means of least square approximation principle. The computer program print-out is in the appendix. The data and the computed results are tabulated in Table 2. It should be noted that "bad" data were purposedly kept for illustration and comparison.

8.1 Heat Flux Effect

At the beginning of this experiment, it is necessary to find out approximately how much heater input power is needed to maintain a contact temperature of 150 F. One way to go about it, is to arbitrary set an input power. The equilibrium temperature distribution will yield the mean contact temperature. A few trial is sufficient to establish the proper input power. For stainless steel, it is about 30 watts. The data obtained in these trials could be used to investigate the heat flux effect on the thermal contact conductance. It should be pointed out that in this experiment, the heat sink temperature was relatively constant and so was the thermal resistance of the specimen. Therefore, heat flux is more or less directly proportional to mean contact temperature (Fig.16).

This result is shown in Fig.(17). It is seen that the contact conductance increases slightly with heat flux or mean contact temperature. The physical reason for this behavior is probably that, at contact, the normal thermal stress, unlike in the case of solid piece of rod, is a function of radial distance. Besides, the inherent minute waviness of the two surfaces, causes an uneven stress distribution and hence the actual contact area. This effect was also pointed out in the results of previous investigators.

8.2 Pressure Effect

Pressure effects were studied in the past experimentally and theoretically. The details are very complicated, however, as a rule of thumb, it is quite certain that the thermal contact conductance increases with applied pressure. The reason is that both the number of contact points and the average size of the contact points increase with applied pressure. The result of this experiment did, as it should, give the right trend. This plot is shown in Fig.(21). The dependence of those two quantities on pressure is related to the surface state.

8.3 Surface Roughness Effect

By intuition, we would conclude that the rougher the contact surfaces the higher the resultant thermal contact resistance. This is because of the larger proportion of void volume in between the two contact surfaces. The experimental results in Fig.(22) does illustrate the heavy dependence of contact conductance on the surface roughness (note: geometric mean roughness is used to characterize the two contact surface). In the same graph, the pressure effect once again stands out quite naturally.

8.4 Vibration Duration Effect

In this test, vibration was applied horizontally to the contact surfaces through a probe which was solidly clamped to the bottom specimen. Preliminary test had shown that the two specimens behaved as a solid bar when vibration was applied to either specimen. That is, the vibrational displacement varied continuously without noticeable abrupt change across the contact. The test was performed at an applied pressure of 3000 psi. With the aid of high quality vibration detector small jump across contact may be found in existence.

This horizontal vibration is believed to have at least three important effects on the contact surfaces. They represent dominant influence at each stage of vibration.

It is assumed that at the beginning, the oscillating shear stress generated.by the vibration will produce a kind of "grinding" action at contact surfaces. This "grinding" action would probably cause material fatigue and yield which in turn reduces the sharp peaks of surface asperities and consequently increase the actual contact area.

As vibration prolongs, the second stage starts. Since the sharp peaks have been reduced gradually, the coefficient of friction between these two contact surfaces will also decrease accordingly. As a result, the two surfaces displace relative to each other in such a manner that the peaks and the valleys on one surface will fit the valleys and the peaks of the other surface. This action would then, increases the coefficient of friction as well as the total contact area and hence the contact conductance will increase (Fig.7).

An opposite effect will become dominant as vibration goes on.. This is the onset of third stage effect, i.e. the oscillating mechanical bending moment which has the effect of giving rise to the oscillating normal stress superimposed on the mean applied normal stress. Schematically its behavior is shown in Fig.(6). The stress distribution as function of time in one cycle is fluctuating about the center line. The maximum amplitude of compressive stress could be much larger than the mean applied stress. Consequently, persistent vibration will cause slight plastic deformation at outer surface in the direction which vibration is applied. Its exagerated sketch is shown in Fig.(8). The stress distribution after the end of vibration will be high in the center and dropping slightly towards the edge in the direction of vibration. This effect is quite undesirable in real thermal contact. Fortunately, this bending moment is negligible in most practical application of thermal contact and hence the third effect does not exist in reality.

It is a known fact that the actual contact area and hence contact conductance increases with normal stress. Since all surfaces have at least some minute waviness, it is, therefore, reasonable to say that the center region contributes less resistance than the circumferential region. In other words, as far as thermal conductance is concerned, the center is more important than the edge of the surface. The net effect can be described in terms of importance concept. The experimental results are shown in Figs. 18, 19 & 20. These curves do give the trend of vibration effect, however, in practical thermal contact the conductance will approach a horizontal asymptote rather than dropping slightly because of the third effect. This is indicated by dashed line in Fig.(23).

8.5 Vibration Amplitude Effect

Experimentally, it is very difficult to study the vibration amplitude effect alone because of the accompanied duration effect. The procedure for this part of experiment is that the equilibrium temperature readings are taken after a five-minute vibration at a certain amplitude which varies from zero to maximum obtainable for that particular frequency of vibration.

The experimental graphs in Figs. 23, 24 & 25 have similar characteristics shown in previous section. However, there are more to it. In each of those figures, a tendency exists that the higher the applied pressure the larger the vibration effect on thermal contact conductance. This might be due to the increasing importance of the second effect mentioned in the previous section. Also the thermal contact conductance drops faster at high vibration amplitude as applied pressure increases. This could be explained as follows: for the same vibrational amplitude at contact, the higher the pressure, the higher the restraining force, in order to maintain the same amplitude, more electrical power is needed to drive the vibrator. In other words, the surface flatness will be distorted faster and hence causes the faster drop in thermal contact conductance at higher pressure.

8.6 Vibration Frequency Effect

In this part of the experiment all controlled variables are fixed except the vibration frequency. It should be noted that the vibration amplitude can be detected only by vibration meter which is not very reliable because of its undue sensitivity to the surrounding disturbances and to temperature at the pickup-head. Also, the vibration displacement amplitude drops drastically with increasing frequency, hence it limits the range of test in frequency and in amplitude.

For the frequency range tested in this part of the experiment (50cps to 250 cps), the amplitude was kept at 0.5 mil(peak to peak). The result is shown in Fig.(26). It is seen that the thermal conductance increases slightly and then decreases. This behavior is similar to that of vibration duration test. One plausible explanation is that it is the number of vibration which has real effect on the distortion of contact surface. Therefore, vibration frequency effect curve can be converted to duration curve with simple shift of horizontal scale or vice versa. This is shown in Fig.(27) as an example. More tests are definitely needed to confirm this speculation.

8.7 <u>Dimensional Analysis Result</u>

The reports of previous experimenters on thermal contact resistance gave no words on the dimensional analysis. It was because that the dimensional analysis was not very successful in thermal contact resistance study. The present result shown in Log-Log graph of Fig.(27) is a sign of some progress. It is seen that the solid line shift to the right for small value of Pi3(=fτ). The crossing between lines in not yet understood. The wide-spread of data-points from the solid line is the consequence of large uncertainty of results. One possible reason is that the errors in measuring roughness and pressure are larger (percentage-wise) than the maximum effects the vibration has on the thermal contact resistance. The other possible reason is that the waviness of the contact surface was assumed to be flat which is not entirely correct because of the small waviness generated by glass-bead blasting and heat treatment while running the tests.

8.8 Possible Experimental Errors

In passing, it is necessary to point out that several experimental errors likely contribute to the distortion of final results. These are:

(1) The temperature equilibrium criteria was arbitrarily based on the graph of the Brown Potentiometer Recorder at the biginning. However it was found later that the Recorder was not sensitive enough to detect slight potential of less than 10 or 15 microvolts. As a result, a new criteria was chosen to base on the stability of the Null Detector's pointer. That is that the equilibrium is assumed reached whenever the pointer deflect less than 2 microvolts in either direction during a period of five minutes. Despite of its arbitrariness, this degree of equilibrium is by no means easy to reach. On the average it required five to six hours. Unfortunately, the amount of uncertainty introduced by this type of equilibrium criteria is not determined.

(2) The fluctuating line voltage is a main cause to the above difficulty. Since this experiment was performed in the MIT Nuclear Reactor Building where the varying demand for electricity during the day gave rise most of the fluctuating which could go as high as ten to fifteen percent daily. This pitfall was partially corrected by using an additional powerstat to control the input voltage to the heaters.

(3) The General Radio's Vibration Meter is a rather crude vibration detecting device. Its 1 3/4" x 1 3/4" pickup (accelerometer type) is just too big for detection at a well-defined position. On top of this, it is very sensitive to environmental disturbance that even the foot-step will cause its meter to deflect. Also, this transistorized device is not operating properly under high ambient temperature condition i.e. above 90 F, hence, a cooling system is provided by circulating water around it. However, no measure can be taken to keep the pickup from getting too hot.

CHAPTER 9

CONCLUSION

In this experiment one pair of SS 303, one pair of Al 2024-T4 and four pairs of SS 416 specimens of different roughness have been tested for various vibration effects on thermal contact resistance. The experimental results indicate that small amplitude vibration tends to increase the total thermal contact conductance by about 5% in most cases. However, persistent large amplitude vibration distorts surface profile to such an extent that the total thermal contact conductance will decrease slightly. One conclusion draws from the experimental results is that under normal circumstance (i.e. in the absence of excessive vibration), the vibration effects are of the second order in comparison with those effects of surface roughness and applied pressure.

It should be pointed out that the conditions under which the tests had been performed were not exactly the same as in the practical situation where both the surface distortion effect and the the effect due to the fact that the thermal contact conductance is function of normal stress the thermal contact conductance is function of normal stress which is not constant when vibration is applied to the contact. This effect can be taken into account only if a set of data for thermal contact conductance vs. the applied stress is available. However, the computation has to be done by numerical integration. Also, the type of vibration which causes the normal stress in the specimen to fluctuate is not investigated in this work. However, this is a good starting point for further study on vibration effects. Also, vibration effects on different materials in contact is highly recommended for future investigation of this phenomenon. Finally, the dimensional analysis should be studied in parallel with the experiment in greater detail. It could become a very useful tool. Since the vibration effects on thermal contact conductance is relatively small, the quality of the experimental data has to be improved and the data should be analyzed by more sophisticated numerical method taking into account the non-linear temperature distribution as well as the axial varying heat flux due to radial heat loss or heat gain, in order to eliminate the masking by the relatively large uncertainty.

APPENDIX

COMPUTER PROGRAM---LEAST SQUARE LINE APPROXIMATION

(FORTRAN II-D)

```
            BTM SPECIMEN    T = A1 + B1*X
            TOP SPECIMEN    T = A1 + B1*X

     COEFFICIENTS A1, B1, A2, B2 ARE SOLVED BY LEAST SQUARE APPROX.


     TEMP DROP ACROSS CONTACT = A1 - A2
     HEAT FLUX = K * IBI(AVG)
     CONTACT CONDUCTANCE = HEAT FLUX/TEMP DROP
```

```
C
C       SW4 ON     PUNCH AND PRINT
C       SW4 OFF    PUNCH ONLY
C
C    NMAX IS TOTAL SETS OF DATA, N IS NUMBER OF POINTS IN EACH SPECIMEN.
C    NO IS RUN NO. OF FIRST DATA
C
      DIMENSION DLNO(76),FNA(76),FNB(76),DT(38),TKHM(38)
      DIMENSION  A(38,2),B(38,2),FLUX(38,2),TKCM(38),THICK(38)
      DIMENSION H(38),D(8),T(304),X(38,2),Y(38,2)
   55 READ 10,N,NMAX,NO,TKO,TK1
      NSUM=2*N
      IMAX=NMAX*NSUM
      READ 11,(D(I),I=1,NSUM)
      READ 12,(T(I),I=1,IMAX)
      I=0
      K=-1
   13 KK=(3+K)/2
      ICHK=0
      L=(1+I+N)/N
      SIGX=0.
      SIGT=0.
```

```
      SIGXT=0.
      SIGXQ=0.
   14 ICHK=ICHK+1
      I=I+1
      M=ICHK+N*(1+K)/2
      SIGX=SIGX+D(M)
      SIGXT=SIGXT+D(M)*T(I)
      SIGT=SIGT+T(I)
      SIGXQ=SIGXQ+D(M)*D(M)
       IF(ICHK-N) 14,15,15
   15 ML=(L+1)/2
       IF(K) 16,17,17
   16 X(ML,1)=D(1)
      X(ML,2)=D(N)
       GO TO 18
   17 Y(ML,2)=D(ICHK+1)
      Y(ML,1)=D(M)
   18 FN=N
      DENO(L)=FN*SIGXQ-SIGX*SIGX
      FNA(L)=SIGT*SIGXQ-SIGX*SIGXT
      FNB(L)=FN*SIGXT-SIGX*SIGT
      B(ML,KK)=FNB(L)/DENO(L)
      A(ML,KK)=FNA(L)/DENO(L)
      K=-K
       IF(I-IMAX) 13,19,19
   19 LMAX=ML
      IF (LMAX-NMAX) 9,21,9
   21 DO 20 L=1,LMAX
      DT(L)=A(L,1)-A(L,2)
      TKH1=TK0+TK1*(A(L,1)+B(L,1)*X(L,1))
      TKH2=TK0+TK1*(A(L,1)+B(L,1)*X(L,2))
      TKC1=TK0+TK1*(A(L,2)+B(L,2)*Y(L,1))
      TKC2=TK0+TK1*(A(L,2)+B(L,2)*Y(L,2))
      TKHM(L)=(TKH1+TKH2)/2.
      TKCM(L)=(TKC1+TKC2)/2.
      FLUX(L,1)=TKHM(L)*ABSF(B(L,1))*12./22.5
      FLUX(L,2)=TKCM(L)*ABSF(B(L,2))*12./22.5
      DT(L)=DT(L)/22.5
      H(L)=(FLUX(L,1)+FLUX(L,2))/(2.*DT(L))
      THICK(L)=((TK0+TK1*A(L,1))+ TK0+TK1*A(L,2))/(2.*H(L))
      THICK(L)=1.0E+03*THICK(L)
C     THICK(L) IS THE EQUIVALENT THICKNESS OF THE METALLIC CONTACT.
C     DT(L) IS THE TEMPERATURE DROP.
      DENO(L)= NO+L-1
   20 CONTINUE
      L=N+1
      DO 81 I=L,NSUM
   81 D(I)=-D(I)
        IF(SENSESWITCH 4)23,22
   23 PRINT 24
      PRINT 26
      PRINT 27
      PRINT 25
      PRINT 28,(D(I),I=1,8)
```

```
      PRINT 29
      PRINT 30
      PRINT 48, TK0,TK1
      PRINT 31
   22 PUNCH 24
      PUNCH 26
      PUNCH 27
      PUNCH 25
      PUNCH 28,(D(I),I=1,8)
      PUNCH 29
      PUNCH 30
      PUNCH 48, TK0, TK1
      PUNCH 31
      I=1
      L=0
   41 L=L+1
      IF=I+7
      II=DENO(L)
        IF (SENSESWITCH 4)44,45
   44 PRINT 32 ,II,(T(IA),IA=I,IF)
   45 PUNCH 32 ,II,(T(IA),IA=I,IF)
      I=I+8
        IF(I-IMAX) 41,41,33
C    PRINT HEADING
   33 PUNCH 34
      PUNCH 1
       DO 3 I=1,LMAX
      T(I)=(A(I,1)+A(I,2))/45.0
C    T(I) IS MEAN CONTACT TEMPERATURE, 22.5 IS THE AVERAGE MICROVOLTS
C    PER DEGREE AND 2 TIMES 22.5 IS 45.
      READ 2, SIGMA,PRES, TAU, FREQ,AMP
C    TO CONSERVE THE MEMORY STORAGE,FNA, FNB,TKCM ARE USED FOR PI-GROUPS
      FNA(I)=(SIGMA*PRES*FREQ)/(8.003*H(I)*T(I))
      FNB(I)=AMP/SIGMA*1000.0
      TKCM(I)=FREQ*TAU*60.0
    3 PUNCH 4,DENO(I),SIGMA, PRES, TAU, FREQ, AMP
        IF(SENSESWITCH 4)46,47
   46 PRINT 35
      PRINT 36
      PRINT 37
      PRINT 49
      PRINT 38
      PRINT 39
      PRINT 40,(DENO(L),FLUX(L,1),FLUX(L,2),DT(L),T(L),
     1 THICK(L),H(L),L=1,LMAX)
   47 PUNCH 34
      PUNCH 35
      PUNCH 36
      PUNCH 37
      PUNCH 49
      PUNCH 38
      PUNCH 39
      PUNCH 40,(DENO(L),FLUX(L,1),FLUX(L,2),DT(L),T(L),
     1 THICK(L),H(L),L=1,LMAX)
```

```
      PUNCH 5
    6 PUNCH 7,(DENO(I), FNA(I),FNB(I),TKCM(I), I=1, LMAX)
      PRINT 43
      PUNCH 34
        GO TO 55
    9 PRINT 42
        GO TO 55
    1 FORMAT (//18X, 20HCONTROLLED VARIABLES//4H RUN 2X,9HROUGHNESS 2X,
     1 8HPRESSURE 2X,4HTIME 2X, 9HFREQUENCY 2X,9HAMPLITUDE/ 5X,
     2 11H(MICROINCH) 2X, 5H(PSI) 4X,5H(MIN) 3X,5H(CPS) 6X,6H(MILS) //)
    2 FORMAT(5F10.2)
    4 FORMAT(I4,2X,F7.2,2X,F8.1,3X,F5.1,2X,I7, 5X,F6.3)
    5 FORMAT(////18X,24HDIMENSIONLESS PARAMETERS///  66H PI1= ROUGHNESS*
     1PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE/        38H PI2=
     2 VIBRATION DISPLACEMENT/ROUGHNESS/34H PI3= VIBRATION FREQUENCY*DUR
     3ATION///2X,7HRUN NO. 10X, 3HPI1 14X, 3HPI2, 14X,3HPI3//)
    7 FORMAT (3X, I4, 8X, E9.3, 8X, E9.3, 8X, E9.3)
   10 FORMAT(3I10,2E10.5)
   11 FORMAT(8F10.5)
   12 FORMAT(8F10.2)
   24 FORMAT(25X,17HEXPERIMENTAL DATA////)
   25 FORMAT(54H LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH/)
   26 FORMAT (/14H SPECIMENS TOP 9X, 9HROUGHNESS )
   27 FORMAT(11X, 3HBTM 9X,    9HROUGHNESS//)
   28 FORMAT  (4F7.4,4F8.4///)
   29 FORMAT  (26H TEMPERATURE IN MICROVOLTS)
   30 FORMAT(48H MEASURED BY 28-GAGE CHROMEL-ALUMEL THERMOCOUPLE/)
   31 FORMAT(/4H RUN 4X,2HT1 5X,2HT2 5X,2HT3 5X,2HT4 5X,2HT5 5X,2HT6
     1 5X, 2HT7 5X,2HT8/)
   32 FORMAT  (I4,1X,8F7.1)
   34 FORMAT  (1H1)
   35 FORMAT(/39H NUMERICAL RESULTS BY IBM 1620 COMPUTER)
   36 FORMAT(36H ASSUMING LINEAR TEMPERATURE PROFILE)
   37 FORMAT(55H AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED)
   38 FORMAT(/4H RUN 3X,6HFLUX A,4X,6HFLUX B,3X,3HD T,2X,5HMEANT 2X,
     1 9HTHICKNESS 2X,11HCONDUCTANCE)
   39 FORMAT(8X,14H(BTU/HR-FT-SQ),4X,3H(F),3X,3H(F),5X,6H(MILS) 1X,
     116H(BTU/HR-FT-SQ-F)//)
   40 FORMAT(I4,F10.1,F10.1,F5.1,F7.1,F10.2,F12.2)
   42 FORMAT (34H PLEASE COUNT THE DATA CARDS AGAIN)
   43 FORMAT (19H READY FOR NEW DATA)
   48 FORMAT (25H THERMAL CONDUCTIVITY K = F8.4, 2H +, F10.8, 4H * T/)
   49 FORMAT(//65H FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM
     1 SPECIMENS./40H D T IS TEMPERATURE DROP ACROSS CONTACT./
     2 39H MEANT IS THE MEAN CONTACT TEMPERATURE./  50H THICKNESS IS THE
     3 EQUIVALENT THICKNESS OF CONTACT./)
      END
```

Table 1 Surface Preparation

Material	Glass bead size (microns)	Blast pressure (psi)	Roughness (μin)
S.S. 416	0-85	50	43
S.S. 416	177-250	50	56
S.S. 416	177-250	70	159
S.S. 416	177-250	100	226
S.S. 416	250-420	50	97
S.S. 416	250-420	100	132
S.S. 416	No blasting at all		6.7

*The glass bead blasting of specimen surfaces were performed at Potters Brothers, Inc., Carlstadt, N.J.

TABLE 2A

EXPERIMENTAL DATA

SPECIMENS TOP SS 303 ROUGHNESS 53.7 MICROINCHUNES
BTM SS 303 ROUGHNESS 28.3 MICROINCHUNES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.3158 1.0150 .6954 .3798 -.3839 -.6965 -1.0072 -1.3169

TEMPERATURE IN MICROVOLTS
MEASURED BY 28-GAGE CHROMEL-ALUMEL THERMOCOUPLE

THERMAL CONDUCTIVITY K = 8.7339 + .00017505 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
1	13538.	12459.	11312.	9950.0	6485.0	4918.0	3405.0	1670.0
2	8937.0	8150.0	7315.0	6457.0	4194.0	3194.0	2268.0	1235.0
3	6957.0	6318.0	5639.0	4968.0	3248.0	2504.0	1874.0	1073.0
4	5733.4	5206.0	4645.6	4097.2	2711.0	2121.6	1586.2	991.8
5	4527.2	4120.5	3688.4	3280.4	2223.8	1786.1	1396.0	977.0
6	4800.0	4359.2	3890.7	3455.5	2330.6	1864.9	1444.0	995.0
7	5049.0	4557.0	4053.0	3569.7	2368.0	1880.0	1426.2	960.0
8	5063.0	4594.0	4095.6	3623.6	2394.4	1898.4	1437.0	958.7
9	5280.2	4814.9	4320.5	3823.2	2528.8	2038.0	1514.5	1005.0
10	5562.6	5068.5	4543.5	4013.8	2623.8	2058.8	1532.6	981.4

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
1	38.90	3055.0	0.0	0	0.000
2	38.90	3055.0	0.0	0	0.000
3	38.90	3055.0	0.0	0	0.000
4	38.90	3055.0	0.0	0	0.000
5	38.90	3055.0	0.0	0	0.000
6	38.90	3055.0	0.0	0	0.000
7	38.90	3055.0	1.0	100	2.000
8	38.90	3055.0	5.0	100	1.100
9	38.90	3055.0	10.0	100	1.550
10	38.90	3055.0	20.0	100	1.350

....

RESULTS

NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A (BTU/HR-FT-SQ)	FLUX B (BTU/HR-FT-SQ)	D T (F)	MEANT (F)	THICKNESS (MILS)	CONDUCTANCE (BTU/HR-FT-SQ-F)
1	21953.1	25877.9	3.6	379.0	1.56	6531.12
2	14228.4	15485.8	2.4	241.5	1.61	6007.90
3	11081.0	11184.7	1.2	184.3	1.05	8988.81
4	8947.3	8844.5	.9	152.0	.96	9706.98
5	6699.4	6385.2	1.8	122.1	2.61	3518.95
6	7258.1	6853.0	1.3	128.2	1.75	5268.22
7	7993.4	7240.1	1.0	131.1	1.23	7484.48
8	7796.8	7382.4	2.4	133.5	3.00	3084.47
9	7907.8	7902.7	3.0	142.2	3.59	2582.85
10	8441.8	8463.6	4.3	148.4	4.76	1956.87

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
1	.000E-99	.000E-99	.000E-99
2	.000E-99	.000E-99	.000E-99
3	.000E-99	.000E-99	.000E-99
4	.000E-99	.000E-99	.000E-99
5	.000E-99	.000E-99	.000E-99
6	.000E-99	.000E-99	.000E-99
7	.151E+01	.514E+02	.600E+04
8	.360E+01	.282E+02	.300E+05
9	.404E+01	.398E+02	.600E+05
10	.511E+01	.347E+02	.120E+06

TABLE 2B

SPECIMENS TOP SS 416 ROUGHNESS 6.9 MICROINCHES
BTM SS 416 ROUGHNESS 6.5 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.1962 .9023 .6199 .3269 -.3188 -.6091 -.9141 -1.2159

THERMAL CONDUCTIVITY K = 13.8550 + .00013293 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
11	4507.5	4103.3	3745.3	3292.9	2349.5	1922.8	1477.7	1009.2
12	5047.7	4606.8	4188.0	3666.3	2541.0	2072.2	1561.2	1031.5
13	5093.0	4637.4	4217.5	3694.5	2548.0	2095.5	1559.6	1040.5
14	4948.0	4506.6	4102.8	3588.2	2464.0	2028.8	1502.6	995.6
15	5019.0	4559.6	4141.3	3611.6	2491.6	2046.0	1504.5	982.0
16	4872.5	4421.0	4019.0	3493.6	2447.0	2005.0	1472.2	961.0
17	4653.0	4226.5	3841.2	3347.2	2355.2	1938.0	1440.5	953.0
18	4694.3	4265.5	3878.8	3381.7	2378.8	1964.0	1454.0	967.4
19	4812.5	4373.5	3973.6	3465.6	2441.0	2012.5	1492.7	996.1
20	5076.5	4609.2	4190.0	3640.3	2566.0	2111.0	1559.5	1068.7
21	4677.0	4255.7	3876.3	3389.2	2404.0	1995.1	1499.2	1020.2
22	4549.5	4141.0	3776.4	3301.2	2352.5	1943.2	1478.4	1017.0
23	4825.6	4387.4	3996.3	3486.5	2477.8	2037.6	1551.7	1048.0
24	5100.8	4636.2	4221.0	3679.3	2602.6	2130.0	1605.7	1071.7
25	5058.0	4600.0	4178.5	3654.8	2581.4	2113.0	1590.3	1064.0
26	4616.2	4196.8	3810.0	3326.5	2392.5	1962.9	1484.5	1002.6
27	4558.2	4144.0	3766.5	3288.8	2370.0	1947.8	1471.2	995.3
28	4642.3	4219.8	3831.0	3346.0	2410.6	1981.2	1496.0	1019.1
29	4695.8	4265.9	3875.7	3380.0	2430.4	1991.5	1503.7	1014.5
30	4749.7	4317.2	3919.0	3414.3	2448.2	2000.8	1522.2	1020.9
31	4791.2	4355.5	3954.2	3449.6	2480.6	2033.8	1542.0	1045.5
32	4861.2	4417.1	4013.2	3498.0	2511.8	2053.8	1560.8	1052.4
33	4797.0	4359.8	3955.8	3453.2	2485.2	2045.6	1557.3	1056.2
34	4775.7	4343.3	3944.7	3447.4	2486.3	2027.3	1570.2	1064.1
35	4737.2	4309.8	3915.8	3415.8	2461.9	2005.0	1552.6	1051.4
36	4349.6	3959.6	3600.7	3143.8	2281.0	1866.5	1455.7	999.0
37	4604.5	4189.8	3807.2	3320.0	2399.0	1957.2	1510.6	1032.0
38	4418.2	4025.2	3663.2	3206.0	2335.9	1916.3	1498.0	1041.5
39	4510.3	4108.3	3736.4	3269.0	2376.9	1948.1	1520.0	1050.9
40	4554.8	4146.6	3766.8	3297.6	2396.5	1961.7	1529.8	1058.4
41	4416.5	4023.9	3660.4	3208.4	2339.4	1928.7	1512.0	1064.2
42	4468.8	4068.3	3697.5	3235.2	2346.5	1929.0	1500.0	1042.7
43	4264.3	3884.7	3534.4	3093.7	2255.1	1851.1	1457.9	1014.0
44	4273.7	3891.7	3539.5	3090.0	2253.6	1847.6	1452.5	1006.5
45	4361.4	3973.9	3606.7	3163.1	2288.5	1871.4	1465.2	1008.3
46	4248.3	3872.5	3511.6	3072.2	2230.1	1824.7	1431.1	987.4
47	4231.6	3857.3	3496.8	3065.7	2231.4	1824.2	1428.9	990.8
48	4362.5	3976.6	3599.4	3155.5	2288.5	1868.3	1453.6	1002.6

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
11	6.71	148.0	0.0	0	0.000
12	6.71	148.0	0.0	0	0.000
13	6.71	148.0	5.0	50	.900
14	6.71	148.0	5.0	50	1.450
15	6.71	148.0	5.0	50	3.100
16	6.71	287.0	0.0	0	0.000
17	6.71	287.0	5.5	50	.650
18	6.71	287.0	5.0	50	1.300
19	6.71	287.0	5.0	50	1.900
20	6.71	287.0	5.0	300	.300
21	6.71	287.0	5.0	300	.450
22	6.71	287.0	5.5	300	.580
23	6.71	287.0	5.0	1000	.230
24	6.71	287.0	5.0	1000	.330
25	6.71	287.0	5.0	1000	.340
26	6.71	3055.0	0.0	0	0.000
27	6.71	3055.0	5.0	50	.420
28	6.71	3055.0	5.0	50	.600
29	6.71	3055.0	5.0	50	.950
30	6.71	3055.0	5.0	300	.320
31	6.71	3055.0	5.0	300	.360
32	6.71	3055.0	5.5	300	.600
33	6.71	3055.0	5.0	1000	.080
34	6.71	3055.0	5.0	1000	.090
35	6.71	3055.0	5.0	1000	.110
36	6.71	6891.0	0.0	0	0.000
37	6.71	6891.0	0.0	0	0.000
38	6.71	6891.0	5.0	50	.420
39	6.71	6891.0	5.3	50	.680
40	6.71	6891.0	5.0	50	.980
41	6.71	6891.0	5.3	300	.160
42	6.71	6891.0	5.3	300	.160
43	6.71	6891.0	5.0	300	.260
44	6.71	6891.0	5.0	300	.260
45	6.71	6891.0	5.0	300	.620
46	6.71	6891.0	5.0	1000	.050
47	6.71	6891.0	5.5	1000	.060
48	6.71	6891.0	5.0	1000	.080

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NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A (BTU/HR-FT-SQ)	FLUX B (BTU/HR-FT-SQ)	D T (F)	MEANT (F)	THICKNESS (MILS)	CONDUCTANCE (BTU/HR-FT-SQ-F)
11	10617.0	11192.6	1.2	126.3	1.65	8615.69
12	12157.1	12644.3	3.8	139.1	4.47	3187.99
13	12300.8	12694.2	4.1	139.9	4.70	3033.64
14	11935.1	12368.7	4.3	135.8	5.15	2767.14
15	12359.1	12718.2	2.6	136.8	3.03	4694.38
16	12073.9	12514.4	.4	133.3	.54	26170.41
17	11426.3	11790.0	.4	127.9	.60	23686.95
18	11488.3	11893.1	.6	129.2	.74	19166.81
19	11807.3	12174.4	.5	132.4	.62	22906.88
20	12597.4	12657.8	.8	138.8	.99	14275.57
21	11270.3	11654.3	.7	129.9	.88	16166.45
22	10905.9	11208.2	.9	126.6	1.16	12201.77
23	11724.2	11979.2	.6	133.5	.80	17787.11
24	12472.3	12845.9	.7	140.7	.89	15900.01
25	12338.4	12737.8	.9	139.6	1.03	13839.32
26	11298.5	11652.4	-1.3	128.0	-1.69	-8406.99
27	11107.4	11532.3	-1.4	126.8	-1.87	-7577.02
28	11358.8	11683.3	-1.4	128.8	-1.81	-7826.78
29	11522.8	11874.1	-1.4	130.1	-1.73	-8230.57
30	11705.1	11937.9	-1.0	131.1	-1.24	-11463.70
31	11766.8	12033.0	-1.2	132.6	-1.49	-9511.05
32	11952.8	12220.8	-1.0	134.4	-1.27	-11198.59
33	11791.8	11980.1	-1.4	132.8	-1.69	-8395.38
34	11652.4	11848.7	-.8	132.5	-1.04	-13632.29
35	11581.7	11746.6	-.7	131.3	-.89	-15960.88
36	10534.5	10663.8	-.9	121.1	-1.24	-11405.41
37	11245.4	11400.3	-.9	127.7	-1.15	-12274.37
38	10599.9	10780.5	-.9	123.7	-1.23	-11551.92
39	10865.3	11045.5	-.9	126.1	-1.23	-11560.11
40	11016.3	11147.1	-1.0	127.0	-1.33	-10681.81
41	10571.1	10633.7	-.7	123.7	-1.00	-14130.29
42	10797.2	10879.1	-.7	124.5	-1.01	-14063.20
43	10225.3	10311.5	-.8	119.3	-1.11	-12754.90
44	10335.0	10360.9	-1.1	119.2	-1.53	-9264.87
45	10497.6	10639.3	-.4	121.6	-.56	-25092.10
46	10294.8	10321.9	-.8	118.2	-1.12	-12577.76
47	10211.3	10310.2	-1.0	118.1	-1.40	-10098.79
48	10592.5	10702.7	-1.0	121.4	-1.37	-10355.72

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
11	.000E-99	.000E-99	.000E-99
12	.000E-99	.000E-99	.000E-99
13	.146E-01	.134E+03	.150E+05
14	.165E-01	.216E+03	.150E+05
15	.965E-02	.461E+03	.150E+05
16	.000E-99	.000E-99	.000E-99
17	.397E-02	.968E+02	.165E+05
18	.485E-02	.193E+03	.150E+05
19	.396E-02	.283E+03	.150E+05
20	.364E-01	.447E+02	.900E+05
21	.343E-01	.670E+02	.900E+05
22	.467E-01	.864E+02	.990E+05
23	.101E-00	.342E+02	.300E+06
24	.107E-00	.491E+02	.300E+06
25	.124E-00	.506E+02	.300E+06
26	.000E-99	.000E-99	.000E-99
27	-.133E-00	.625E+02	.150E+05
28	-.126E-00	.894E+02	.150E+05
29	-.119E-00	.141E+03	.150E+05
30	-.511E-00	.476E+02	.900E+05
31	-.608E-00	.536E+02	.900E+05
32	-.510E-00	.894E+02	.990E+05
33	-.229E+01	.119E+02	.300E+06
34	-.141E+01	.134E+02	.300E+06
35	-.122E+01	.163E+02	.300E+06
36	.000E-99	.000E-99	.000E-99
37	.000E-99	.000E-99	.000E-99
38	-.202E-00	.625E+02	.150E+05
39	-.198E-00	.101E+03	.159E+05
40	-.212E-00	.146E+03	.150E+05
41	-.990E-00	.238E+02	.954E+05
42	-.989E-00	.238E+02	.954E+05
43	-.113E+01	.387E+02	.900E+05
44	-.156E+01	.387E+02	.900E+05
45	-.567E-00	.923E+02	.900E+05
46	-.388E+01	.745E+01	.300E+06
47	-.484E+01	.894E+01	.330E+06
48	-.459E+01	.119E+02	.300E+06

TABLE 2C

SPECIMENS TOP AL 2024 T4 ROUGHNESS 202.7 MICROINCHES
BTM AL 2024 T4 ROUGHNESS 281.2 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.1087 .8058 .5044 .1952 -.3811 -.6947 -.9953 -1.3100

THERMAL CONDUCTIVITY K = 67.3446 + .00339168 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
49	4212.4	3872.7	3572.5	3222.8	2337.5	1947.0	1631.5	1276.0
50	4670.2	4286.4	3949.8	3549.5	2554.2	2113.2	1754.5	1345.2
51	4440.0	4087.8	3766.4	3387.3	2441.6	2028.7	1686.2	1304.9
52	4372.6	4027.0	3715.7	3340.7	2416.9	2005.2	1668.0	1297.5
53	4421.6	4069.3	3749.1	3377.7	2432.0	2009.0	1663.6	1287.6
54	4424.6	4071.8	3754.4	3385.2	2433.3	2007.2	1659.4	1286.9
55	4456.0	4100.3	3779.9	3406.4	2445.2	2015.6	1665.5	1286.8
56	4514.7	4158.1	3828.2	3466.8	2478.8	2041.9	1684.3	1300.0
57	4081.0	3838.0	3622.0	3348.0	2125.4	1831.7	1584.5	1333.6
58	3982.7	3743.1	3526.9	3269.0	2058.2	1766.5	1524.4	1278.0
59	4006.4	3761.4	3544.6	3285.9	2061.4	1767.8	1522.8	1271.4
60	3894.6	3665.0	3464.4	3218.2	2015.3	1740.0	1509.6	1272.0
61	4121.5	3873.4	3655.4	3396.0	2132.0	1832.0	1580.1	1323.7
62	4067.9	3835.4	3624.4	3374.2	2108.0	1808.6	1569.2	1318.2
63	4076.5	3833.1	3621.6	3371.0	2106.0	1813.0	1565.2	1312.6

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
49	238.90	3055.0	0.0	0	0.000
50	238.90	3055.0	2.0	500	.090
51	238.90	3055.0	3.0	500	.060
52	238.90	3055.0	4.5	500	.070
53	238.90	3055.0	3.0	500	.070
54	238.90	3055.0	5.1	500	.070
55	238.90	3055.0	6.0	500	.070
56	238.90	3055.0	7.0	500	.070
57	238.90	287.0	0.0	0	0.000
58	238.90	287.0	1.5	500	.180
59	238.90	287.0	2.0	500	.190
60	238.90	287.0	2.5	500	2.000
61	238.90	287.0	3.5	500	.190
62	238.90	287.0	5.0	500	.180
63	238.90	287.0	5.0	500	.180

NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

RUN	FLUX A (BTU/HR-FT-SQ)	FLUX B (BTU/HR-FT-SQ)	D T (F)	MEANT (F)	THICKNESS (MILS)	CONDUCTANCE (BTU/HR-FT-SQ-F)
49	45830.8	44413.5	11.6	128.3	19.84	3887.42
50	52722.1	50912.9	12.7	141.1	19.15	4078.11
51	49198.3	47765.5	12.4	134.7	19.90	3900.35
52	48059.9	46997.2	12.1	133.1	19.78	3917.38
53	48773.9	48057.5	12.4	134.3	19.93	3892.32
54	48552.8	48160.6	12.7	134.5	20.47	3790.80
55	49082.8	48663.0	12.8	135.3	20.43	3800.11
56	49258.1	49588.9	13.4	137.5	21.20	3670.10
57	33865.8	33153.7	34.0	125.3	78.17	983.86
58	32925.5	32555.8	33.7	121.9	79.06	969.44
59	33245.4	32961.7	34.0	122.4	78.93	971.59
60	31052.5	30980.6	34.3	119.7	84.76	902.27
61	33630.9	33836.1	35.4	126.5	80.87	952.18
62	32144.3	32954.3	36.3	125.5	85.86	895.81
63	32646.6	33191.8	35.8	125.4	83.75	918.38

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
49	.000E-99	.000E-99	.000E-99
50	.792E+02	.376E-00	.600E+05
51	.867E+02	.251E-00	.900E+05
52	.874E+02	.293E-00	.135E+06
53	.871E+02	.293E-00	.900E+05
54	.894E+02	.293E-00	.153E+06
55	.886E+02	.293E-00	.180E+06
56	.903E+02	.293E-00	.210E+06
57	.000E-99	.000E-99	.000E-99
58	.362E+02	.753E-00	.450E+05
59	.360E+02	.795E-00	.600E+05
60	.396E+02	.837E+01	.750E+05
61	.355E+02	.795E-00	.105E+06
62	.380E+02	.753E-00	.150E+06
63	.371E+02	.753E-00	.150E+06

TABLE 2D

SPECIMENS TOP SS 416 ROUGHNESS 36.5 MICROINCHES
BTM SS 416 ROUGHNESS 42.5 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.2029 .9019 .6037 .3102 -.3221 -.6078 -.9140 -1.2197

THERMAL CONDUCTIVITY K = 13.8550 + .00013293 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
64	4913.2	4480.3	4066.4	3624.4	2581.2	2150.4	1739.5	1273.8
65	4067.6	3719.7	3387.5	3033.5	2198.2	1855.2	1527.5	1156.0
66	4900.6	4461.2	4037.5	3585.1	2537.5	2092.4	1679.1	1205.5
67	4230.2	3856.7	3500.0	3118.5	2241.0	1866.4	1525.6	1127.2
68	4134.2	3771.2	3421.2	3049.2	2190.8	1825.3	1493.0	1103.5
69	3898.0	3561.2	3237.5	2894.0	2078.5	1744.2	1434.8	1074.8
70	4352.2	3969.9	3597.2	3204.4	2279.4	1892.5	1541.7	1128.4
71	4298.7	3922.5	3556.0	3169.1	2256.4	1875.7	1530.4	1123.4
72	3991.5	3645.4	3309.9	2954.4	2125.1	1778.5	1460.5	1089.2
73	3987.8	3642.9	3305.1	2948.8	2111.2	1765.5	1447.7	1076.3
74	3924.2	3586.4	3258.5	2910.5	2106.5	1770.5	1457.4	1094.1
75	3957.1	3616.1	3285.1	2936.2	2109.6	1771.8	1457.1	1092.7
76	3897.8	3562.7	3235.1	2891.0	2083.0	1748.0	1440.2	1081.5
77	3860.4	3525.9	3195.2	2852.3	2102.3	1765.9	1452.9	1094.1
78	3853.7	3520.4	3188.5	2846.7	2095.8	1760.8	1450.3	1091.8
79	3903.2	3560.7	3223.4	2874.6	2110.1	1768.3	1450.4	1083.5
80	3906.2	3568.6	3230.7	2879.8	2115.0	1771.5	1454.3	1087.2
81	3894.5	3555.4	3219.0	2871.2	2109.0	1767.4	1450.7	1085.5
82	3831.0	3504.2	3180.5	2845.3	2113.2	1783.2	1479.5	1127.1
83	4072.8	3719.8	3368.4	3004.3	2209.8	1851.8	1521.5	1138.6
84	3845.5	3514.8	3186.5	2847.8	2107.0	1774.9	1464.8	1108.5
85	3841.0	3510.8	3183.8	2844.9	2105.8	1773.8	1464.3	1108.1
86	3846.3	3517.3	3192.2	2855.8	2100.7	1770.8	1460.6	1107.8
87	3861.0	3529.0	3201.2	2862.0	2101.1	1766.6	1456.1	1099.2
88	3737.2	3417.3	3101.1	2775.1	2042.7	1721.5	1423.7	1079.6
89	3801.8	3474.9	3150.8	2818.2	2070.9	1742.6	1437.7	1085.0
90	4134.7	3768.9	3406.7	3033.2	2237.0	1868.9	1526.7	1130.7
91	3993.8	3646.4	3303.9	2945.8	2188.6	1837.9	1511.2	1135.2
92	4057.1	3704.7	3353.1	2987.9	2216.0	1856.6	1525.4	1142.0
93	4044.2	3692.6	3340.2	2977.0	2207.5	1849.2	1518.9	1136.7
94	3937.7	3596.5	3258.4	2905.2	2162.5	1817.1	1496.2	1129.9
95	3919.2	3579.1	3242.3	2893.4	2155.5	1812.0	1493.3	1128.0
96	4006.9	3658.4	3313.0	2952.7	2194.2	1841.6	1513.1	1137.1
97	4039.1	3688.7	3341.8	2980.4	2213.0	1857.2	1528.6	1150.4
98	3819.9	3491.6	3164.6	2828.9	2114.2	1782.4	1474.8	1123.5
99	3666.6	3355.1	3044.2	2725.5	2048.0	1732.3	1442.4	1108.7
100	4241.0	3869.6	3500.7	3118.0	2307.8	1928.1	1568.8	1173.0

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
64	39.20	287.0	0.0	0	0.000
65	39.20	287.0	0.0	0	0.000
66	39.20	287.0	5.0	50	.700
67	39.20	287.0	5.0	50	1.190
68	39.20	287.0	5.0	50	3.100
69	39.20	287.0	5.0	300	.170
70	39.20	287.0	5.0	300	.190
71	39.20	287.0	5.0	300	.190
72	39.20	287.0	5.0	300	.400
73	39.20	287.0	0.0	0	0.000
74	39.20	287.0	5.0	1000	.080
75	39.20	287.0	5.0	1000	.090
76	39.20	287.0	5.0	1000	.090
77	39.20	3055.0	0.0	0	0.000
78	39.20	3055.0	5.0	50	.480
79	39.20	3055.0	5.0	50	.700
80	39.20	3055.0	5.0	50	.840
81	39.20	3055.0	5.0	50	.840
82	39.20	3055.0	5.3	300	.160
83	39.20	3055.0	5.0	300	.270
84	39.20	3055.0	5.0	300	.310
85	39.20	3055.0	5.0	300	.310
86	39.20	3055.0	0.0	0	0.000
87	39.20	3055.0	5.0	1000	.050
88	39.20	3055.0	5.0	1000	.060
89	39.20	3055.0	5.0	1000	.100
90	39.20	6890.0	0.0	0	0.000
91	39.20	6890.0	5.0	50	.280
92	39.20	6890.0	5.0	50	.470
93	39.20	6890.0	5.0	50	.730
94	39.20	6890.0	5.0	300	.110
95	39.20	6890.0	5.0	300	.210
96	39.20	6890.0	5.0	300	.290
97	39.20	6890.0	0.0	0	0.000
98	39.20	6890.0	5.0	1000	.040
99	39.20	6890.0	5.0	1000	.050
100	39.20	6890.0	5.0	1000	.060

NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A	FLUX B	D T	MEANT	THICKNESS	CONDUCTANCE
	(BTU/HR-FT-SQ)		(F)	(F)	(MILS)	(BTU/HR-FT-SQ-F)
64	11061.8	10872.7	6.3	138.4	8.26	1725.78
65	8817.1	8647.2	5.1	116.6	8.30	1710.58
66	11291.4	11057.0	5.9	136.5	7.57	1883.90
67	9488.5	9217.1	4.8	119.3	7.42	1913.46
68	9258.3	8993.7	4.8	116.6	7.53	1884.59
69	8551.2	8303.8	5.3	110.7	9.04	1568.69
70	9817.5	9523.4	5.8	122.1	8.59	1654.22
71	9657.1	9373.2	5.8	120.8	8.75	1624.17
72	8842.3	8569.1	5.0	113.0	8.20	1729.62
73	8862.4	8560.2	5.3	112.6	8.76	1619.42
74	8638.2	8380.4	4.5	111.7	7.63	1858.96
75	8703.9	8418.2	5.3	112.3	8.90	1592.95
76	8582.6	8283.5	5.0	110.7	8.50	1668.01
77	8597.5	8348.1	2.2	110.3	3.84	3688.27
78	8591.6	8310.0	2.4	110.0	4.03	3516.54
79	8774.7	8498.5	2.3	110.9	3.78	3751.40
80	8759.5	8505.9	2.4	111.2	3.98	3560.84
81	8731.1	8472.1	2.3	110.8	3.90	3635.32
82	8405.9	8160.6	2.2	110.3	3.78	3752.60
83	9130.3	8870.4	2.4	116.1	3.79	3745.09
84	8510.6	8269.0	2.1	110.3	3.64	3887.54
85	8494.7	8261.4	2.1	110.2	3.62	3914.92
86	8447.4	8226.9	2.9	110.3	5.08	2792.04
87	8520.5	8294.7	3.0	110.5	5.07	2793.94
88	8199.1	7968.9	2.8	107.2	5.05	2801.63
89	8388.6	8159.1	2.8	108.8	4.86	2915.65
90	9416.2	9164.9	1.3	117.3	2.06	6871.84
91	8943.8	8726.9	1.3	114.3	2.12	6668.19
92	9134.8	8894.0	1.3	115.9	2.16	6557.45
93	9120.5	8867.2	1.3	115.4	2.08	6825.16
94	8809.3	8554.6	1.2	112.8	2.10	6749.39
95	8753.2	8510.5	1.2	112.4	1.97	7167.44
96	8999.8	8759.4	1.2	114.6	1.99	7114.13
97	9040.8	8802.0	1.5	115.6	2.40	5902.76
98	8454.0	8204.6	1.2	110.0	2.14	6619.77
99	8019.7	7771.4	1.1	106.2	2.13	6644.89
100	9607.5	9425.9	1.2	120.8	1.93	7360.98

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
64	.000E-99	.000E-99	.000E-99
65	.000E-99	.000E-99	.000E-99
66	.273E-00	.178E+02	.150E+05
67	.307E-00	.303E+02	.150E+05
68	.319E-00	.790E+02	.150E+05
69	.242E+01	.433E+01	.900E+05
70	.208E+01	.484E+01	.900E+05
71	.214E+01	.484E+01	.900E+05
72	.215E+01	.102E+02	.900E+05
73	.000E-99	.000E-99	.000E-99
74	.676E+01	.204E+01	.300E+06
75	.785E+01	.229E+01	.300E+06
76	.761E+01	.229E+01	.300E+06
77	.000E-99	.000E-99	.000E-99
78	.193E+01	.122E+02	.150E+05
79	.179E+01	.178E+02	.150E+05
80	.188E+01	.214E+02	.150E+05
81	.185E+01	.214E+02	.150E+05
82	.108E+02	.408E+01	.954E+05
83	.103E+02	.688E+01	.900E+05
84	.104E+02	.790E+01	.900E+05
85	.104E+02	.790E+01	.900E+05
86	.000E-99	.000E-99	.000E-99
87	.484E+02	.127E+01	.300E+06
88	.497E+02	.153E+01	.300E+06
89	.471E+02	.255E+01	.300E+06
90	.000E-99	.000E-99	.000E-99
91	.221E+01	.714E+01	.150E+05
92	.222E+01	.119E+02	.150E+05
93	.214E+01	.186E+02	.150E+05
94	.132E+02	.280E+01	.900E+05
95	.125E+02	.535E+01	.900E+05
96	.124E+02	.739E+01	.900E+05
97	.000E-99	.000E-99	.000E-99
98	.463E+02	.102E+01	.300E+06
99	.478E+02	.127E+01	.300E+06
100	.379E+02	.153E+01	.300E+06

TABLE 2E

SPECIMENS TOP SS 416 ROUGHNESS 159.2 MICROINCHES
BTM SS 416 ROUGHNESS 153.5 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.1980 .9095 .6248 .3332 -.3477 -.6271 -.9207 -1.2132

THERMAL CONDUCTIVITY K = 13.8550 + .00013293 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
101	3794.5	3536.2	3287.7	3007.2	1997.3	1771.9	1471.8	1174.4
102	4463.3	4144.0	3832.6	3486.0	2247.6	1967.6	1592.0	1222.0
103	4058.2	3771.3	3494.4	3186.7	2078.6	1830.2	1495.6	1166.0
104	4191.9	3892.6	3604.3	3282.1	2130.0	1870.2	1523.7	1179.8
105	4268.8	3966.3	3670.5	3343.9	2165.6	1902.7	1547.5	1202.5
106	4251.2	3953.2	3657.1	3330.0	2159.7	1897.2	1542.2	1194.0
107	4117.5	3830.0	3546.4	3234.1	2108.3	1856.6	1516.3	1183.0
108	4296.1	3991.3	3691.9	3361.1	2178.4	1910.9	1551.2	1198.2
109	4286.5	3984.9	3689.2	3361.7	2186.7	1921.4	1564.2	1214.8
110	4212.1	3915.0	3625.3	3303.0	2156.5	1895.5	1544.5	1201.3
111	4178.6	3882.3	3592.9	3269.3	2124.2	1862.8	1510.5	1166.2
112	4340.7	4025.4	3718.5	3375.0	2182.0	1906.5	1533.1	1170.0
113	4410.0	4059.8	3715.6	3329.8	2280.2	1971.2	1554.4	1136.2
114	4328.4	3985.8	3645.6	3264.7	2237.0	1934.0	1526.1	1119.7
115	4389.5	4036.1	3695.6	3309.0	2262.6	1957.7	1540.1	1128.0
116	4196.1	3862.9	3540.3	3174.7	2186.0	1898.1	1504.1	1115.0
117	4192.9	3860.3	3538.9	3174.2	2182.6	1895.0	1501.7	1112.1
118	4018.6	3706.5	3398.6	3051.4	2111.3	1837.6	1466.5	1096.3
119	4285.0	3949.0	3614.5	3241.6	2223.6	1926.4	1523.7	1122.5
120	4152.1	3831.6	3513.2	3155.7	2189.5	1905.8	1521.5	1140.5
121	4131.0	3814.3	3501.1	3149.5	2174.8	1894.1	1513.8	1136.8
122	4282.6	3951.2	3625.4	3258.8	2254.4	1963.1	1569.2	1180.6
123	4273.6	3942.1	3617.7	3252.6	2254.4	1963.5	1570.0	1182.1
124	4374.8	4032.4	3694.2	3314.0	2273.8	1969.9	1560.8	1158.1
125	4156.9	3825.0	3499.8	3134.8	2175.8	1884.7	1493.9	1108.4
126	4087.0	3756.0	3433.0	3070.2	2119.0	1832.8	1445.3	1062.7
127	4104.5	3776.1	3454.9	3094.1	2149.5	1862.7	1477.0	1099.5
128	3969.0	3656.8	3351.5	3006.7	2112.5	1841.4	1477.3	1115.3
129	3932.1	3622.5	3320.0	2979.7	2079.3	1810.2	1449.2	1093.5
130	4317.0	3968.9	3626.7	3245.8	2235.4	1932.7	1525.4	1124.9
131	4357.6	4005.8	3658.2	3273.6	2251.6	1945.5	1532.2	1126.7
132	4317.7	3969.7	3627.1	3244.0	2231.7	1927.7	1518.3	1116.1
133	4330.8	3983.3	3639.5	3260.4	2236.4	1933.0	1525.0	1124.2
134	4366.6	4013.5	3666.9	3281.4	2252.5	1945.8	1532.6	1127.1
135	4249.2	3913.4	3579.6	3212.1	2230.3	1936.7	1539.4	1147.6
136	4229.1	3891.4	3556.2	3187.3	2198.4	1904.0	1506.8	1116.9

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
101	156.20	287.0	0.0	0	0.000
102	156.20	287.0	5.0	1000	.050
103	156.20	287.0	5.0	1000	.055
104	156.20	287.0	5.0	1000	.070
105	156.20	287.0	0.0	0	0.000
106	156.20	287.0	5.0	300	.135
107	156.20	287.0	5.0	300	.210
108	156.20	287.0	5.0	300	.410
109	156.20	287.0	0.0	0	0.000
110	156.20	287.0	5.0	50	.630
111	156.20	287.0	5.0	50	1.650
112	156.20	287.0	5.0	50	2.300
113	156.20	3055.0	0.0	0	0.000
114	156.20	3055.0	5.0	1000	.045
115	156.20	3055.0	5.0	1000	.070
116	156.20	3055.0	5.0	1000	.085
117	156.20	3055.0	0.0	0	0.000
118	156.20	3055.0	5.0	300	.210
119	156.20	3055.0	5.0	300	.320
120	156.20	3055.0	5.0	300	.350
121	156.20	3055.0	0.0	0	0.000
122	156.20	3055.0	5.0	50	.520
123	156.20	3055.0	5.0	50	1.140
124	156.20	3055.0	5.0	50	1.600
125	156.20	6891.0	0.0	0	0.000
126	156.20	6891.0	5.0	1000	.055
127	156.20	6891.0	5.0	1000	.060
128	156.20	6891.0	5.0	1000	.065
129	156.20	6891.0	0.0	0	0.000
130	156.20	6891.0	5.0	300	.125
131	156.20	6891.0	5.0	300	.270
132	156.20	6891.0	5.0	300	.380
133	156.20	6891.0	0.0	0	0.000
134	156.20	6891.0	5.0	50	.450
135	156.20	6891.0	5.0	50	.790
136	156.20	6891.0	5.0	50	1.410

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NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A (BTU/HR-FT-SQ)	FLUX B	D T (F)	MEANT (F)	THICKNESS (MILS)	CONDUCTANCE (BTU/HR-FT-SQ-F)
101	6919.2	7192.2	16.1	112.4	32.40	437.89
102	8642.6	8981.0	19.1	128.9	31.00	459.24
103	7679.6	7983.9	17.2	118.3	31.32	453.54
104	8023.6	8310.5	17.9	121.6	31.19	455.86
105	8169.2	8435.9	18.5	123.8	31.77	447.65
106	8139.5	8455.3	18.2	123.4	31.23	455.44
107	7796.1	8099.5	17.6	120.1	31.50	451.17
108	8261.2	8581.5	18.2	124.5	30.85	461.15
109	8169.6	8511.2	18.2	124.7	31.14	456.85
110	8023.4	8363.0	17.5	122.7	30.52	465.93
111	8021.7	8385.6	17.4	121.3	30.30	469.20
112	8528.7	8864.2	17.6	125.0	28.83	493.40
113	9543.6	10010.5	6.8	126.5	9.91	1435.84
114	9394.8	9776.0	6.6	124.0	9.89	1437.42
115	9534.3	9938.1	6.8	125.6	9.96	1427.51
116	9001.1	9376.4	6.4	120.8	9.99	1422.16
117	8976.2	9370.5	6.6	120.7	10.29	1380.95
118	8518.0	8876.1	6.3	116.3	10.31	1377.03
119	9214.8	9635.8	6.8	123.2	10.31	1378.97
120	8788.1	9180.6	6.3	120.4	10.05	1413.86
121	8654.3	9083.6	7.1	120.0	11.50	1235.66
122	9035.9	9403.6	7.1	124.2	10.99	1293.44
123	9009.1	9390.9	6.9	124.0	10.69	1330.04
124	9370.5	9769.8	7.3	125.9	10.91	1303.82
125	9010.2	9338.7	5.2	119.6	8.17	1739.50
126	8956.5	9239.3	5.1	116.8	8.08	1757.27
127	8902.5	9188.1	5.1	118.0	8.11	1749.87
128	8468.3	8719.7	4.7	115.2	7.82	1815.33
129	8379.6	8620.3	5.3	113.8	9.00	1575.70
130	9458.5	9721.2	5.8	123.4	8.71	1631.22
131	9578.0	9850.0	5.8	124.4	8.60	1653.61
132	9479.6	9765.9	5.8	123.3	8.64	1644.48
133	9457.5	9736.2	6.4	123.7	9.53	1491.35
134	9585.7	9853.7	6.1	124.6	9.03	1574.37
135	9159.6	9479.3	5.6	122.5	8.60	1651.79
136	9198.9	9466.7	5.9	121.2	9.02	1576.14

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
101	.000E-99	.000E-99	.000E-99
102	.945E+02	.320E-00	.300E+06
103	.104E+03	.352E-00	.300E+06
104	.100E+03	.448E-00	.300E+06
105	.000E-99	.000E-99	.000E-99
106	.298E+02	.864E-00	.900E+05
107	.310E+02	.134E+01	.900E+05
108	.292E+02	.262E+01	.900E+05
109	.000E-99	.000E-99	.000E-99
110	.489E+01	.403E+01	.150E+05
111	.491E+01	.105E+02	.150E+05
112	.453E+01	.147E+02	.150E+05
113	.000E-99	.000E-99	.000E-99
114	.334E+03	.288E-00	.300E+06
115	.332E+03	.448E-00	.300E+06
116	.346E+03	.544E-00	.300E+06
117	.000E-99	.000E-99	.000E-99
118	.111E+03	.134E+01	.900E+05
119	.105E+03	.204E+01	.900E+05
120	.105E+03	.224E+01	.900E+05
121	.000E-99	.000E-99	.000E-99
122	.185E+02	.332E+01	.150E+05
123	.180E+02	.729E+01	.150E+05
124	.181E+02	.102E+02	.150E+05
125	.000E-99	.000E-99	.000E-99
126	.654E+03	.352E-00	.300E+06
127	.650E+03	.384E-00	.300E+06
128	.642E+03	.416E-00	.300E+06
129	.000E-99	.000E-99	.000E-99
130	.200E+03	.800E-00	.900E+05
131	.196E+03	.172E+01	.900E+05
132	.198E+03	.243E+01	.900E+05
133	.000E-99	.000E-99	.000E-99
134	.342E+02	.288E+01	.150E+05
135	.332E+02	.505E+01	.150E+05
136	.351E+02	.902E+01	.150E+05

TABLE 2F

SPECIMENS TOP SS 416 ROUGHNESS 235.8 MICROINCHES
BTM SS 416 ROUGHNESS 217.2 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.2154 .9212 .6449 .3623 -.3353 -.6232 -.9155 -1.2107

THERMAL CONDUCTIVITY K = 13.8550 + .00013293 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
137	4158.5	3868.5	3599.4	3322.6	2207.0	1922.6	1625.7	1314.2
138	3993.3	3719.7	3462.3	3199.1	2128.3	1854.3	1596.5	1272.6
139	3761.7	3509.3	3272.2	3022.0	2029.8	1774.9	1538.7	1238.3
140	4055.9	3777.6	3515.0	3237.8	2147.4	1862.6	1601.8	1268.8
141	4140.0	3861.0	3598.5	3320.6	2225.0	1938.1	1674.5	1333.6
142	4021.2	3753.4	3500.0	3228.8	2173.3	1894.8	1638.2	1310.6
143	4097.5	3817.0	3555.0	3274.5	2197.6	1907.9	1646.3	1302.1
144	3887.7	3628.2	3384.8	3125.0	2109.2	1839.4	1597.0	1276.8
145	4063.5	3787.2	3529.3	3253.5	2185.2	1898.6	1638.1	1296.2
146	4083.2	3805.0	3545.2	3267.1	2182.7	1894.0	1631.8	1289.5
147	3898.4	3628.6	3376.0	3107.0	2063.7	1784.1	1533.2	1204.5
148	3877.6	3608.7	3357.2	3089.1	2057.7	1778.5	1527.8	1202.1
149	4050.5	3767.5	3498.0	3223.2	2123.5	1834.4	1544.8	1217.4
150	4020.9	3701.1	3402.2	3099.1	2162.5	1842.5	1524.4	1164.2
151	4033.6	3713.6	3418.1	3104.3	2159.8	1831.6	1529.6	1151.6
152	4060.1	3738.3	3441.3	3126.4	2177.6	1847.5	1551.2	1165.0
153	4090.5	3765.8	3465.7	3148.4	2191.7	1858.2	1558.7	1169.4
154	4070.8	3748.8	3450.5	3135.5	2186.1	1855.5	1559.1	1177.2
155	3992.4	3671.8	3374.1	3059.6	2121.7	1793.2	1500.3	1121.1
156	3974.6	3655.7	3360.1	3047.8	2115.3	1788.1	1498.0	1119.2
157	4033.7	3709.5	3408.6	3090.0	2142.7	1809.9	1515.9	1130.2
158	4050.9	3729.2	3430.2	3113.7	2156.6	1826.2	1535.1	1159.3
159	4050.1	3728.4	3428.6	3110.7	2161.9	1831.0	1539.5	1163.8
160	4121.5	3792.1	3487.1	3162.8	2189.6	1850.7	1552.8	1168.1
161	4230.8	3890.8	3573.8	3240.8	2234.8	1882.7	1574.8	1173.9
162	4087.6	3752.8	3441.2	3114.1	2175.7	1831.0	1528.5	1133.1
163	4048.3	3719.4	3414.8	3089.4	2175.1	1835.2	1538.0	1147.8
164	4116.1	3777.7	3465.4	3132.5	2199.2	1851.6	1548.4	1149.4
165	4040.5	3712.7	3405.0	3080.3	2170.1	1830.8	1534.6	1144.5
166	4062.6	3736.2	3429.6	3106.1	2184.8	1846.7	1552.4	1166.7
167	4136.8	3801.1	3493.4	3164.8	2231.5	1887.2	1587.9	1196.5
168	4136.4	3801.1	3493.4	3164.8	2231.5	1887.2	1587.9	1196.5
169	4129.0	3792.6	3489.0	3160.3	2232.9	1890.9	1591.0	1201.9
170	4137.5	3802.2	3498.9	3170.2	2246.8	1905.5	1606.6	1220.4
171	4086.1	3755.3	3452.7	3126.7	2217.0	1877.7	1582.1	1197.8
172	4109.6	3776.2	3468.7	3140.8	2223.2	1880.1	1582.9	1193.7
173	4218.6	3872.7	3554.3	3214.7	2263.2	1907.5	1599.1	1195.0

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
137	226.10	287.0	0.0	0	0.000
138	226.10	287.0	5.0	1000	.040
139	226.10	287.0	5.0	1000	.050
140	226.10	287.0	5.4	1000	.060
141	226.10	287.0	0.0	0	0.000
142	226.10	287.0	5.0	1000	.040
143	226.10	287.0	5.0	300	.150
144	226.10	287.0	5.0	300	.270
145	226.10	287.0	5.0	300	.370
146	226.10	287.0	0.0	0	0.000
147	226.10	287.0	5.0	50	.800
148	226.10	287.0	5.0	50	1.900
149	226.10	287.0	5.0	50	3.600
150	226.10	3055.0	0.0	0	0.000
151	226.10	3055.0	5.0	1000	.030
152	226.10	3055.0	5.0	1000	.040
153	226.10	3055.0	5.0	1000	.060
154	226.10	3055.0	0.0	0	0.000
155	226.10	3055.0	5.0	300	.180
156	226.10	3055.0	5.0	300	.270
157	226.10	3055.0	5.0	300	.370
158	226.10	3055.0	0.0	0	0.000
159	226.10	3055.0	5.0	50	.450
160	226.10	3055.0	5.0	50	1.150
161	226.10	3055.0	5.0	50	1.550
162	226.10	6891.0	0.0	0	0.000
163	226.10	6891.0	5.0	1000	.030
164	226.10	6891.0	5.0	1000	.040
165	226.10	6891.0	5.0	1000	.050
166	226.10	6891.0	0.0	0	0.000
167	226.10	6891.0	5.0	300	.120
168	226.10	6891.0	5.0	300	.180
169	226.10	6891.0	5.0	300	.280
170	226.10	6891.0	0.0	0	0.000
171	226.10	6891.0	5.0	50	.430
172	226.10	6891.0	5.0	50	1.200
173	226.10	6891.0	5.0	50	1.410

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NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A	FLUX B	D T	MEANT	THICKNESS	CONDUCTANCE
	(BTU/HR-FT-SQ)		(F)	(F)	(MILS)	(BTU/HR-FT-SQ-F)
137	7495.9	7661.3	18.3	122.6	34.51	412.03
138	7116.9	7271.0	17.8	118.2	35.31	402.37
139	6608.7	6715.4	16.6	112.1	35.50	399.65
140	7327.4	7455.9	18.1	119.5	34.84	407.82
141	7343.4	7567.3	18.0	123.2	34.48	412.51
142	7093.2	7324.8	17.3	120.0	34.23	415.20
143	7368.3	7591.8	17.1	121.5	32.64	435.60
144	6818.6	7051.0	16.6	116.3	34.14	416.00
145	7250.1	7538.1	17.1	120.9	32.90	432.04
146	7305.7	7574.5	17.6	121.1	33.75	421.16
147	7075.1	7275.6	16.9	114.8	33.46	424.33
148	7047.4	7246.9	16.5	114.3	32.80	432.75
149	7419.8	7739.2	17.6	118.8	33.09	429.35
150	8258.1	8523.6	6.9	116.7	11.84	1199.16
151	8310.3	8558.4	7.3	116.8	12.37	1147.56
152	8351.8	8579.2	7.3	117.7	12.39	1145.76
153	8430.1	8663.1	7.4	118.5	12.32	1153.11
154	8369.0	8551.5	7.4	118.0	12.55	1131.69
155	8341.1	8473.6	7.1	114.9	12.11	1171.75
156	8285.9	8431.4	7.1	114.5	12.10	1173.15
157	8440.6	8569.6	7.2	116.0	12.03	1180.29
158	8384.6	8446.2	8.0	116.7	13.64	1041.32
159	8404.3	8453.7	7.6	116.8	12.93	1097.84
160	8579.4	8652.1	8.0	118.6	13.20	1075.90
161	8872.6	8984.3	8.1	121.3	13.01	1092.56
162	8713.6	8825.0	5.7	117.2	9.31	1525.29
163	8574.1	8693.9	5.2	116.7	8.70	1631.40
164	8799.1	8884.1	5.2	118.1	8.48	1674.65
165	8592.1	8677.9	5.0	116.3	8.36	1697.65
166	8561.1	8616.4	5.8	117.2	9.60	1479.27
167	8695.2	8762.9	5.7	119.5	9.40	1511.39
168	8691.9	8762.9	5.7	119.5	9.42	1508.35
169	8657.1	8733.8	5.6	119.5	9.23	1539.13
170	8645.7	8697.0	5.6	120.0	9.18	1547.03
171	8575.9	8630.7	5.2	118.4	8.70	1631.40
172	8666.5	8714.5	5.2	118.8	8.59	1654.29
173	8987.5	9044.0	5.4	121.3	8.57	1657.78

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
137	.000E-99	.000E-99	.000E-99
138	.170E+03	.176E-00	.300E+06
139	.180E+03	.221E-00	.300E+06
140	.166E+03	.265E-00	.324E+06
141	.000E-99	.000E-99	.000E-99
142	.162E+03	.176E-00	.300E+06
143	.459E+02	.663E-00	.900E+05
144	.502E+02	.119E+01	.900E+05
145	.465E+02	.163E+01	.900E+05
146	.000E-99	.000E-99	.000E-99
147	.831E+01	.353E+01	.150E+05
148	.819E+01	.840E+01	.150E+05
149	.794E+01	.159E+02	.150E+05
150	.000E-99	.000E-99	.000E-99
151	.643E+03	.132E-00	.300E+06
152	.639E+03	.176E-00	.300E+06
153	.631E+03	.265E-00	.300E+06
154	.000E-99	.000E-99	.000E-99
155	.192E+03	.796E-00	.900E+05
156	.192E+03	.119E+01	.900E+05
157	.189E+03	.163E+01	.900E+05
158	.000E-99	.000E-99	.000E-99
159	.336E+02	.199E+01	.150E+05
160	.338E+02	.508E+01	.150E+05
161	.325E+02	.685E+01	.150E+05
162	.000E-99	.000E-99	.000E-99
163	.102E+04	.132E-00	.300E+06
164	.983E+03	.176E-00	.300E+06
165	.985E+03	.221E-00	.300E+06
166	.000E-99	.000E-99	.000E-99
167	.323E+03	.530E-00	.900E+05
168	.323E+03	.796E-00	.900E+05
169	.317E+03	.123E+01	.900E+05
170	.000E-99	.000E-99	.000E-99
171	.503E+02	.190E+01	.150E+05
172	.495E+02	.530E+01	.150E+05
173	.483E+02	.623E+01	.150E+05

TABLE 2G

SPECIMENS TOP SS 416 ROUGHNESS 235.8 MICROINCHES
BTM SS 416 ROUGHNESS 217.2 MICROINCHES

LOCATION OF THERMOCOUPLE FROM CONTACT SURFACE IN INCH

1.2154 .9212 .6449 .3623 -.3353 -.6232 -.9155 -1.2107

TEMPERATURE IN MICROVOLTS
MEASURED BY 28-GAGE CHROMEL-ALUMEL THERMOCOUPLE

THERMAL CONDUCTIVITY K = 13.8550 + .00013293 * T

RUN	T1	T2	T3	T4	T5	T6	T7	T8
174	4312.4	3962.1	3639.1	3294.2	2286.7	1926.7	1614.9	1202.0
175	4162.5	3826.4	3515.1	3182.7	2213.1	1866.6	1566.4	1169.7
176	4050.9	3762.0	3499.2	3161.5	2267.0	1975.2	1725.0	1328.2
177	4098.2	3810.5	3547.0	3163.9	2267.5	1976.6	1728.4	1335.1
178	4109.1	3821.8	3550.9	3160.0	2280.0	1938.8	1734.1	1338.4
179	4080.9	3795.3	3526.5	3147.1	2258.1	1966.4	1718.6	1323.2
180	4089.7	3804.0	3535.5	3153.5	2261.7	1969.1	1720.9	1326.2
181	4227.8	3928.9	3649.7	3254.3	2320.6	2013.7	1753.4	1344.0
182	3915.3	3606.9	3321.0	3021.3	2103.4	1788.0	1513.3	1142.2

CONTROLLED VARIABLES

RUN	ROUGHNESS (MICROINCH)	PRESSURE (PSI)	TIME (MIN)	FREQUENCY (CPS)	AMPLITUDE (MILS)
174	226.10	3055.0	0.0	0	0.000
175	226.10	3055.0	5.0	1000	.120
176	226.10	3055.0	5.0	750	.120
177	226.10	3055.0	5.0	50	.500
178	226.10	3055.0	5.0	100	.500
179	226.10	3055.0	5.0	150	.500
180	226.10	3055.0	5.0	200	.500
181	226.10	3055.0	5.0	250	.450
182	226.10	3055.0	0.0	0	0.000

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NUMERICAL RESULTS BY IBM 1620 COMPUTER
ASSUMING LINEAR TEMPERATURE PROFILE
AVERAGE THERMAL CONDUCTIVITY AND AVERAGE FLUX ARE USED

FLUX A,FLUX B ARE AVERAGE HEAT FLUX IN TOP AND BOTTOM SPECIMENS.
D T IS TEMPERATURE DROP ACROSS CONTACT.
MEANT IS THE MEAN CONTACT TEMPERATURE.
THICKNESS IS THE EQUIVALENT THICKNESS OF CONTACT.

RUN	FLUX A	FLUX B	D T	MEANT	THICKNESS	CONDUCTANCE
	(BTU/HR-FT-SQ)		(F)	(F)	(MILS)	(BTU/HR-FT-SQ-F)
174	9123.0	9181.7	7.3	123.6	11.44	1242.69
175	8769.6	8828.3	7.1	119.5	11.49	1236.88
176	7901.6	7902.9	7.6	120.9	13.72	1036.04
177	8267.9	7848.4	7.7	120.8	13.58	1046.13
178	8407.4	7805.4	7.6	120.4	13.48	1054.16
179	8276.5	7866.0	7.2	120.2	12.78	1112.18
180	8295.7	7871.8	7.3	120.4	12.98	1094.84
181	8636.0	8223.6	7.8	123.9	13.30	1069.11
182	7991.5	8123.2	7.6	113.6	13.46	1054.07

DIMENSIONLESS PARAMETERS

PI1= ROUGHNESS*PRESSURE*FREQUENCY/CONDUCTANCE*CONTACT TEMPERATURE
PI2= VIBRATION DISPLACEMENT/ROUGHNESS
PI3= VIBRATION FREQUENCY*DURATION

RUN NO.	PI1	PI2	PI3
174	.000E-99	.000E-99	.000E-99
175	.583E+03	.530E-00	.300E+06
176	.516E+03	.530E-00	.225E+06
177	.341E+02	.221E+01	.150E+05
178	.679E+02	.221E+01	.300E+05
179	.968E+02	.221E+01	.450E+05
180	.130E+03	.221E+01	.600E+05
181	.162E+03	.199E+01	.750E+05
182	.000E-99	.000E-99	.000E-99

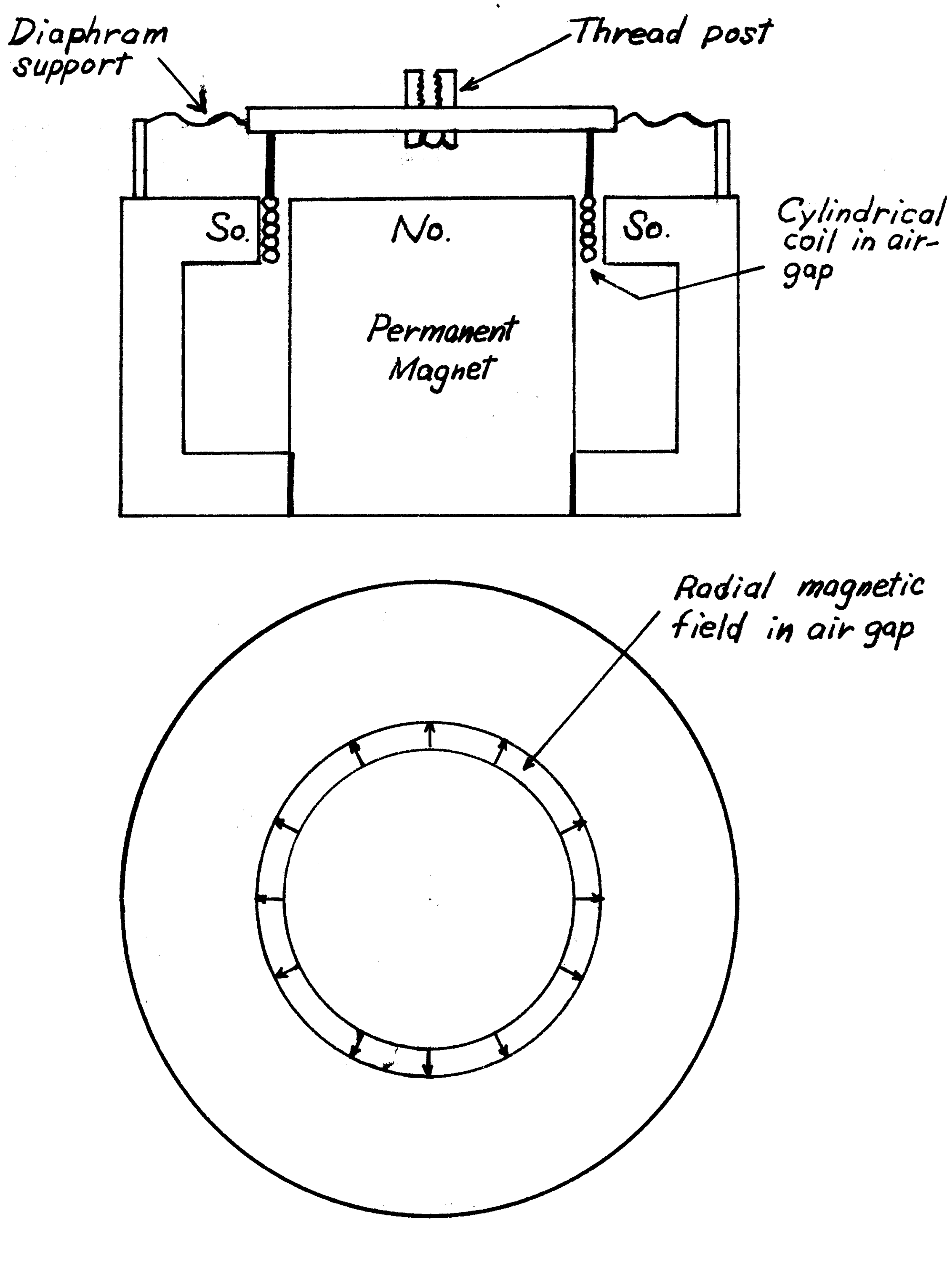


Fig. 1 Schematic Diagram of Vibration Generator

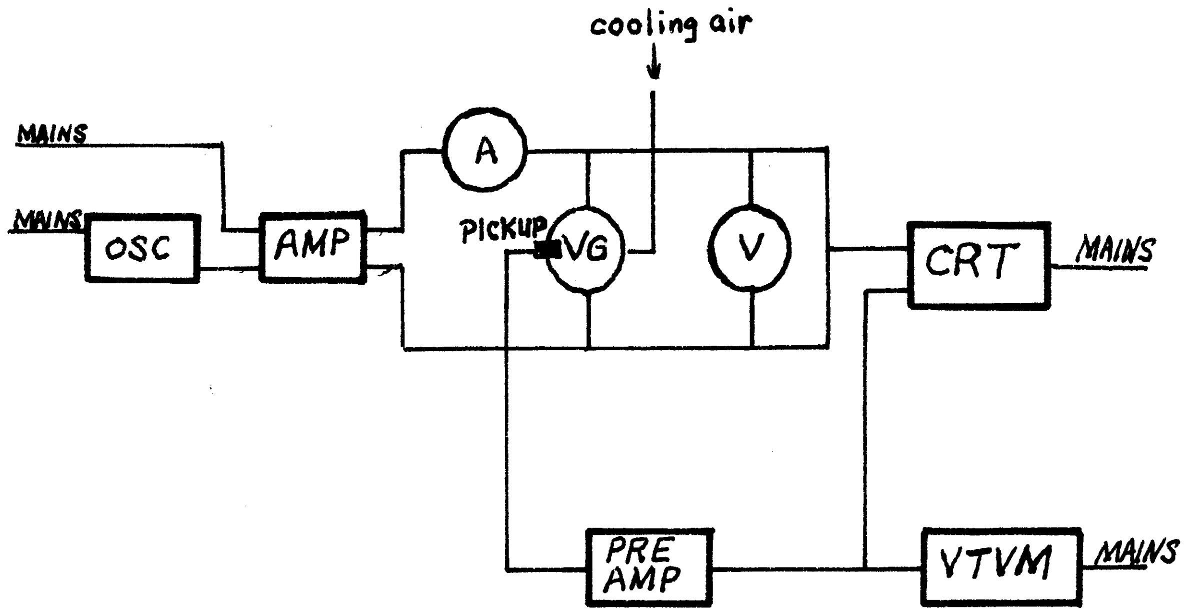


Fig. 2 Typical layout of Drive and Monitoring Equipment

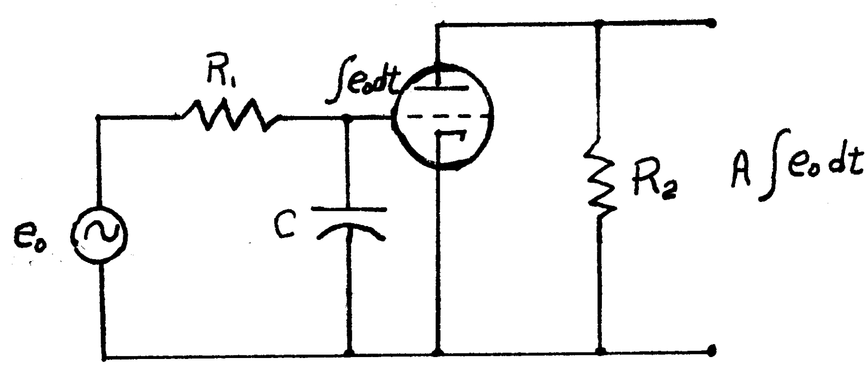


Fig. 3 *Integrating Circuit*

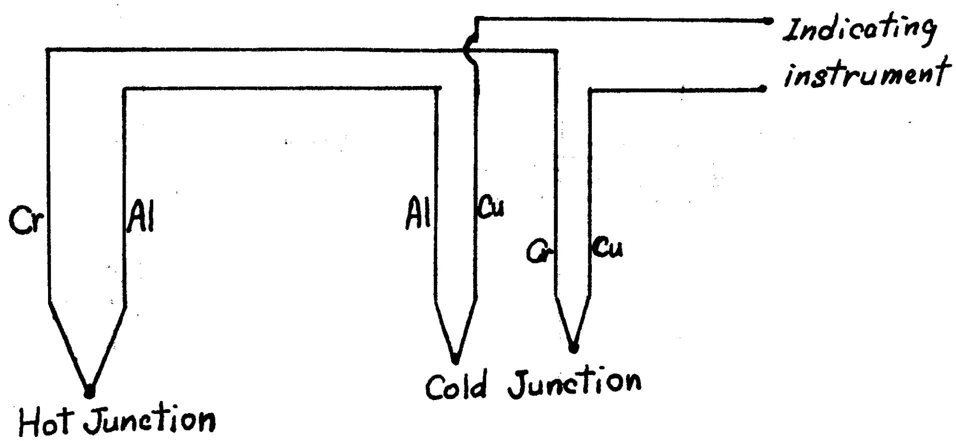


Fig. 4 Thermocouple Circuit

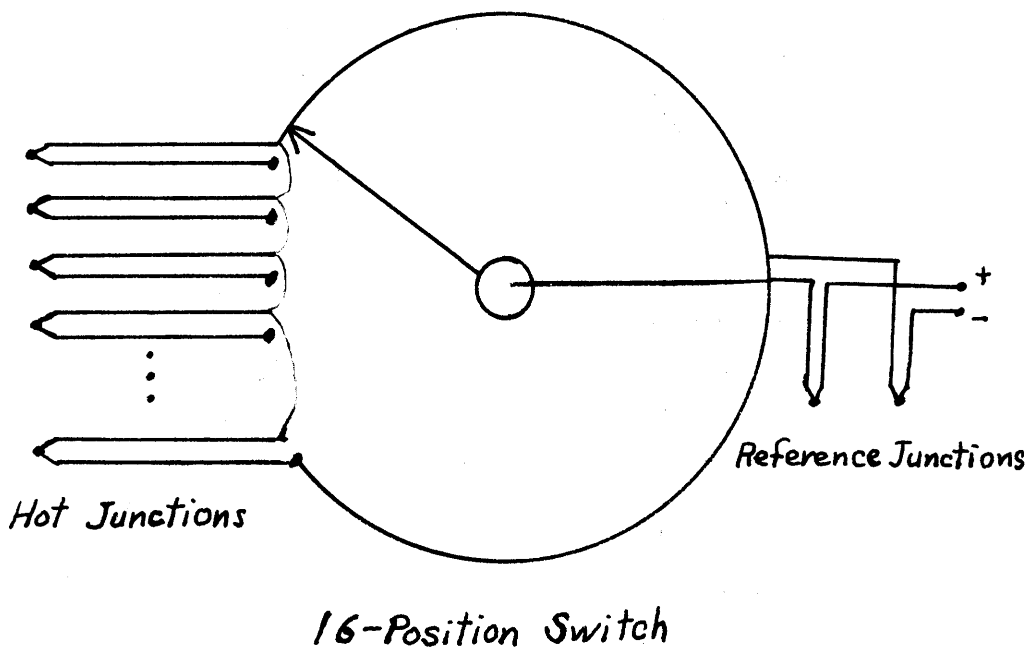
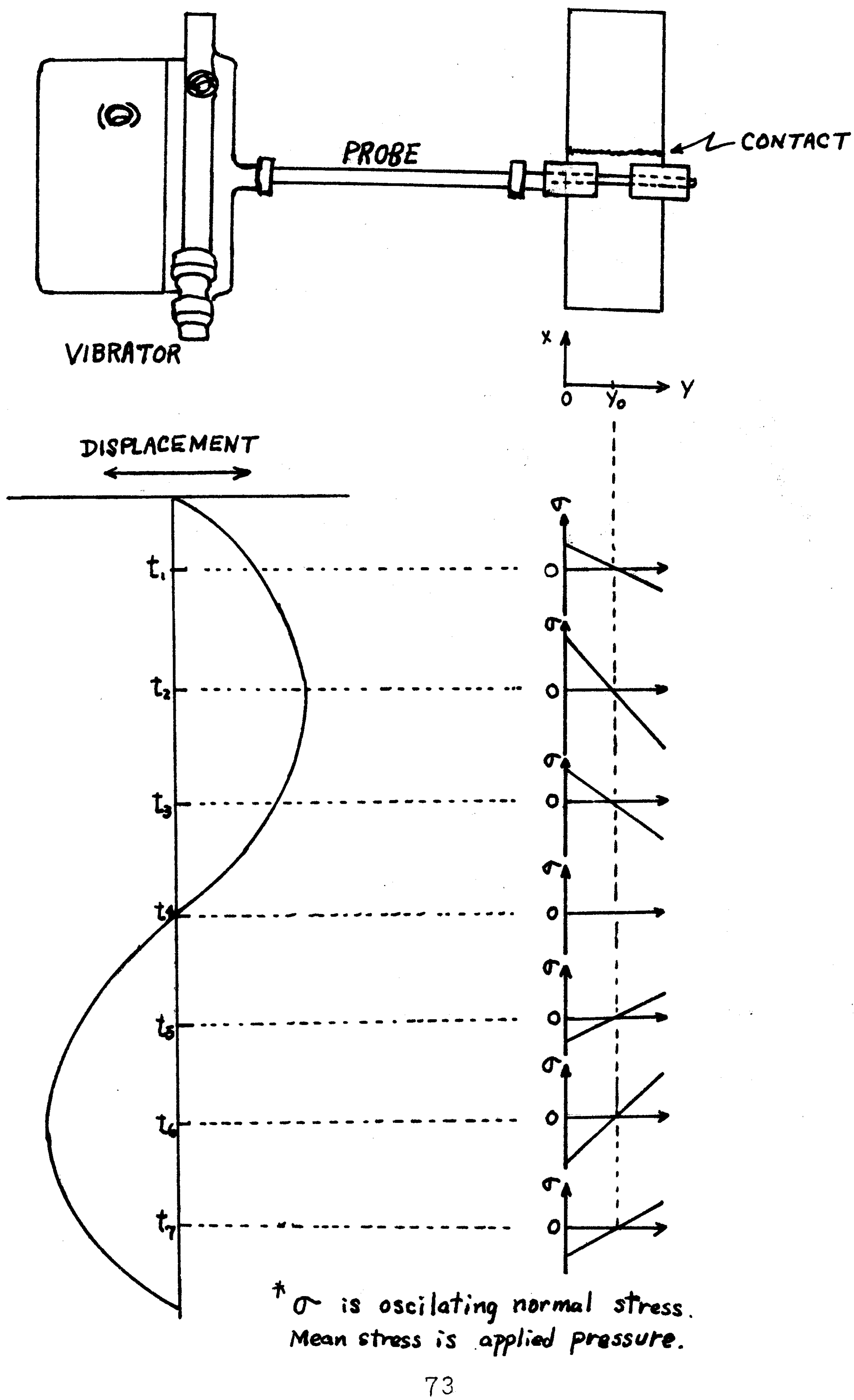


Fig. 5 Schematic connection diagram

Fig. 6



* σ is oscilating normal stress.
Mean stress is applied pressure.

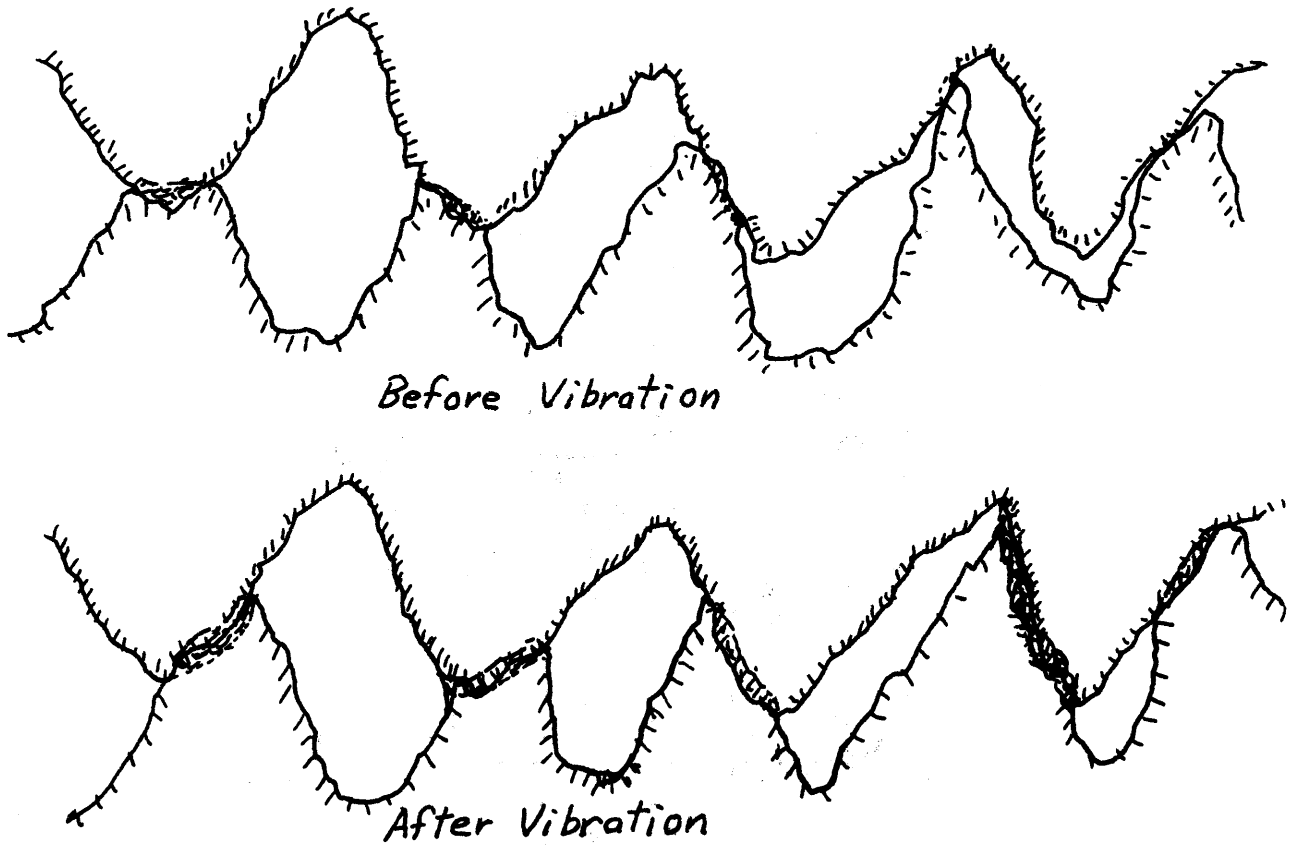


Fig. 7

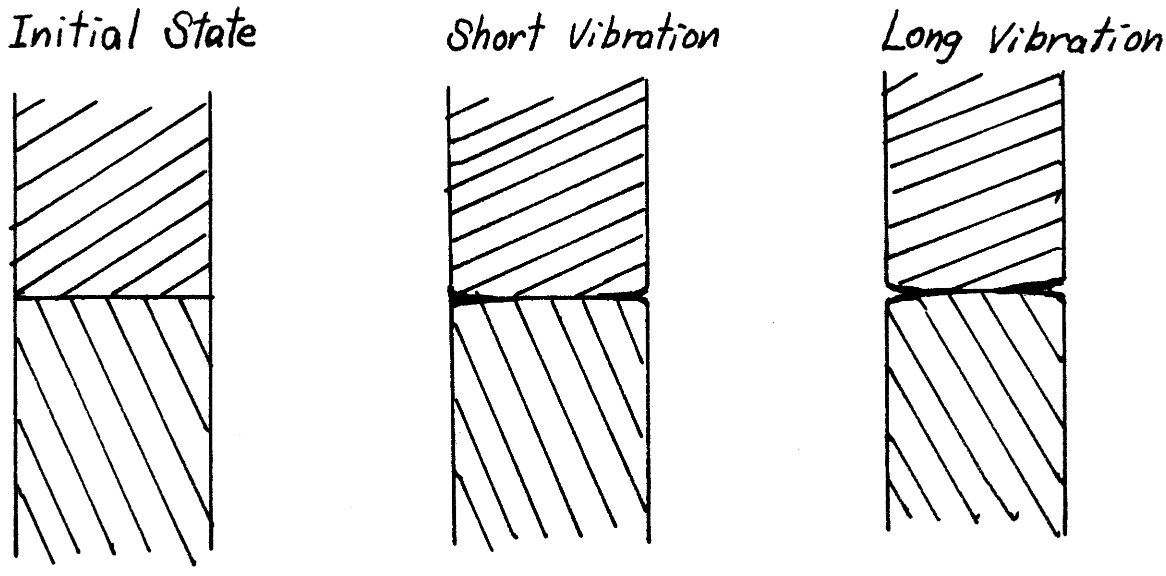
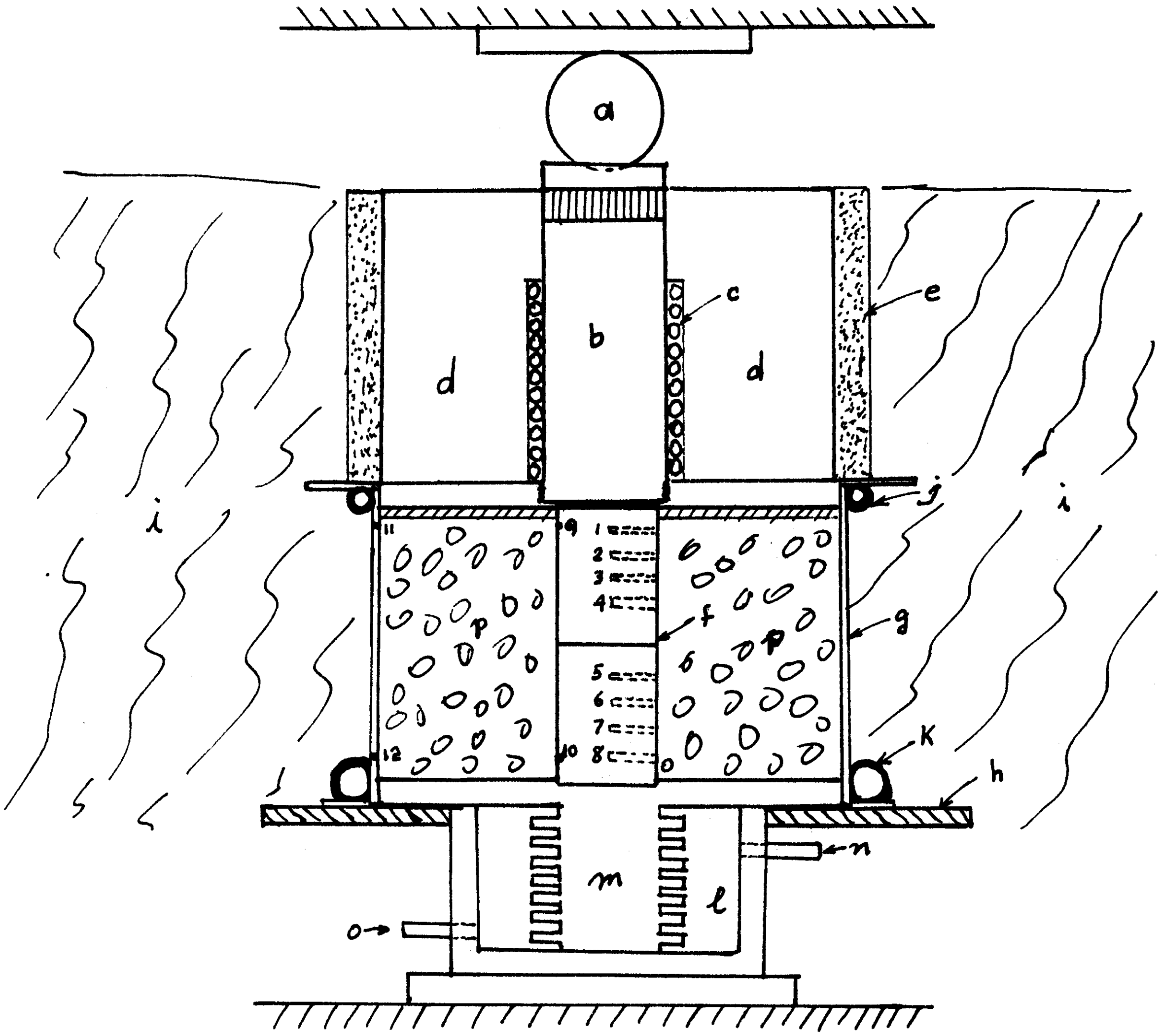


Fig. 8 VIBRATION DURATION EFFECTS



a--Steel ball
b--Heater core
c--Heating coil
d--Refractory brick
e--Asbestos insulation
f--Test specimens
g--Guard ring
h--Supporting plate
i--Fibre glass insulation
j--Guard ring heater
k--Guard ring cooler
l--Main cooler
m--Copper core
n--Water inlet
o--Water outlet
p--Glass wool insulation

Fig. 9 Cross-sectional view of Heater and Cooler

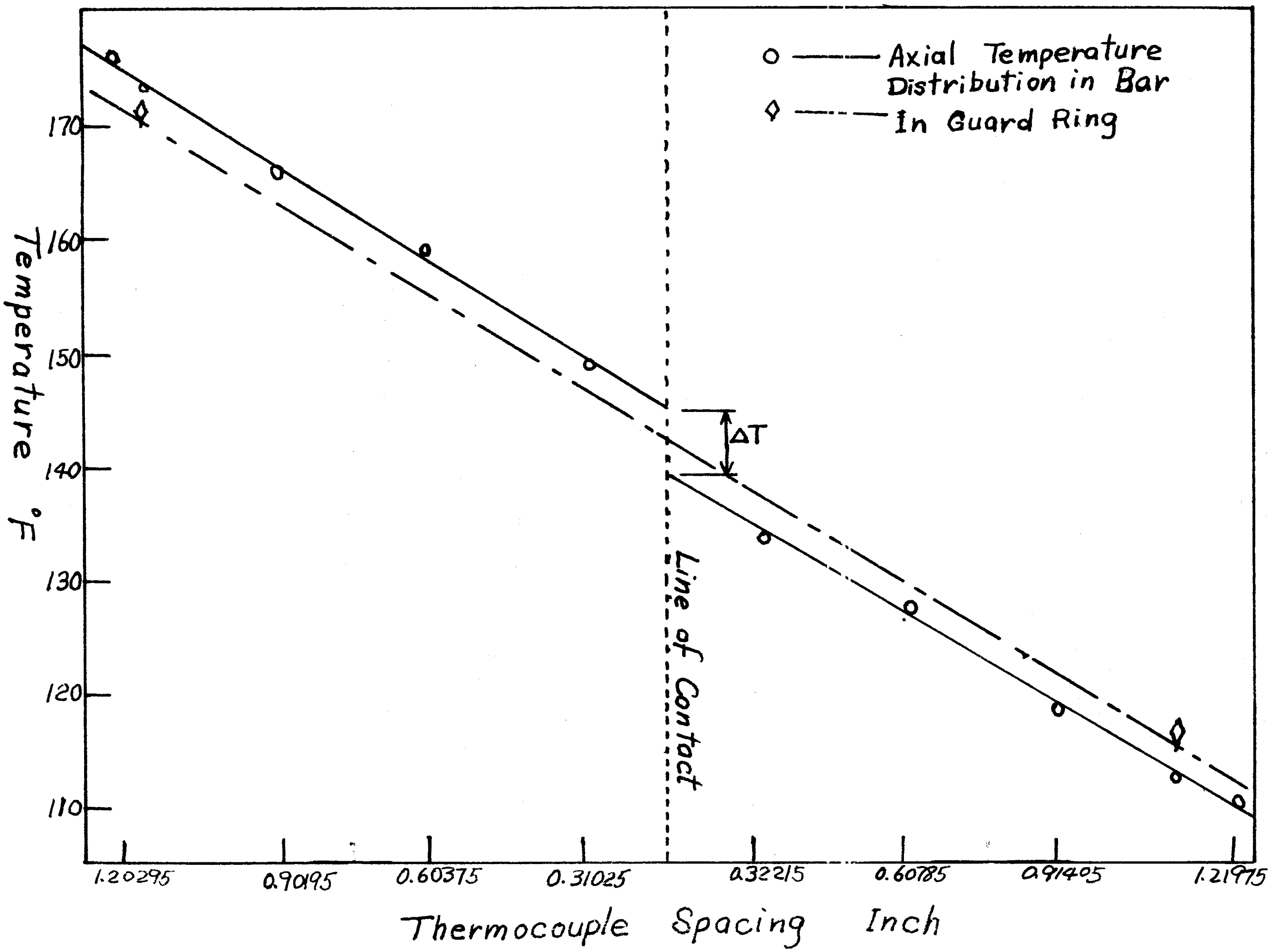


Fig. 10 Typical Temperature Profiles

Fig. 11

RUN 100

$T = A_1 + B_1 X$

T.C. No.	X_i	T_i	X_i^2	$X_i T_i$
1	1.20295	4241.0	1.44709	5101.711
2	0.90195	3869.6	0.8.351	3490.186
3	0.60275	3500.7	0.36451	2113.548
4	0.31025	3118.0	0.09625	967.359
N	ΣX_i	ΣT_i	ΣX_i^2	$\Sigma X_i T_i$
4	3.0189	14729.3	2.72137	11672.804

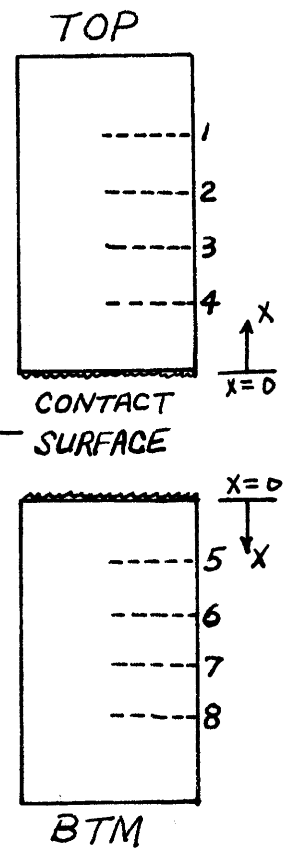
$D = N\Sigma X^2 - (\Sigma X_i)^2 = 10.885 - 9.113 = 1.7717$

$N_A = \Sigma T_i \Sigma X_i^2 - \Sigma X_i \Sigma T_i X_i = 40083.8 - 35239.0 = 4844.84$

$N_B = \Sigma T_i X_i \cdot N - \Sigma X_i \Sigma T_i = 46691.2 - 44466.2 = 2224.93$

$A_1 = N_A / D = 2726.54$

$B_1 = N_B / D = 1255.80$



$T = A_2 + B_2 X$

T.C. No.	X_i	T_i	X_i^2	$X_i T_i$
5	0.32215	2307.8	0.10378	743.458
6	0.60785	1928.1	0.36948	1171.996
7	0.91405	1568.8	0.835487	1433.962
8	1.21975	1173.0	1.48779	1430.767
N	ΣX_i	ΣT_i	ΣX_i^2	$\Sigma X_i T_i$
4	3.0638	6977.7	2.79654	4780.183

$D = N\Sigma X_i^2 - (\Sigma X_i)^2 = 11.18616 - 9.38687 = 1.79929$

$N_A = \Sigma T_i \Sigma X_i^2 - \Sigma X_i \Sigma T_i X_i = 4846.381$

$N_B = N \Sigma T_i X_i - \Sigma X_i \Sigma T_i = -2257.545$

$A_2 = N_A / D = 2698.396$

$B_2 = N_B / D = 1254.686$

$\Delta T = A_1 - A_2 = 28.148\ \mu v = 1.25\ ^{\circ}F$

$(q/A)_{TOP} = \bar{K}_1 |B_1| = 17769.6\ \frac{\text{Btu-}\mu\text{v}}{\text{Hr-Ft-In}}$

$(q/B)_{BTM} = \bar{K}_2 |B_2| = 17565.6\ \frac{\text{Btu-}\mu\text{v}}{\text{Hr-Ft-In}}$

$h = (q/A)_{AVG} / \Delta T = 628.7\ \frac{\text{Btu}}{\text{Hr-Ft-In}} = 7360\ \frac{\text{Btu}}{\text{Hr-Ft}^2\text{-}^{\circ}\text{F}}$

MAIN HEATER CORE

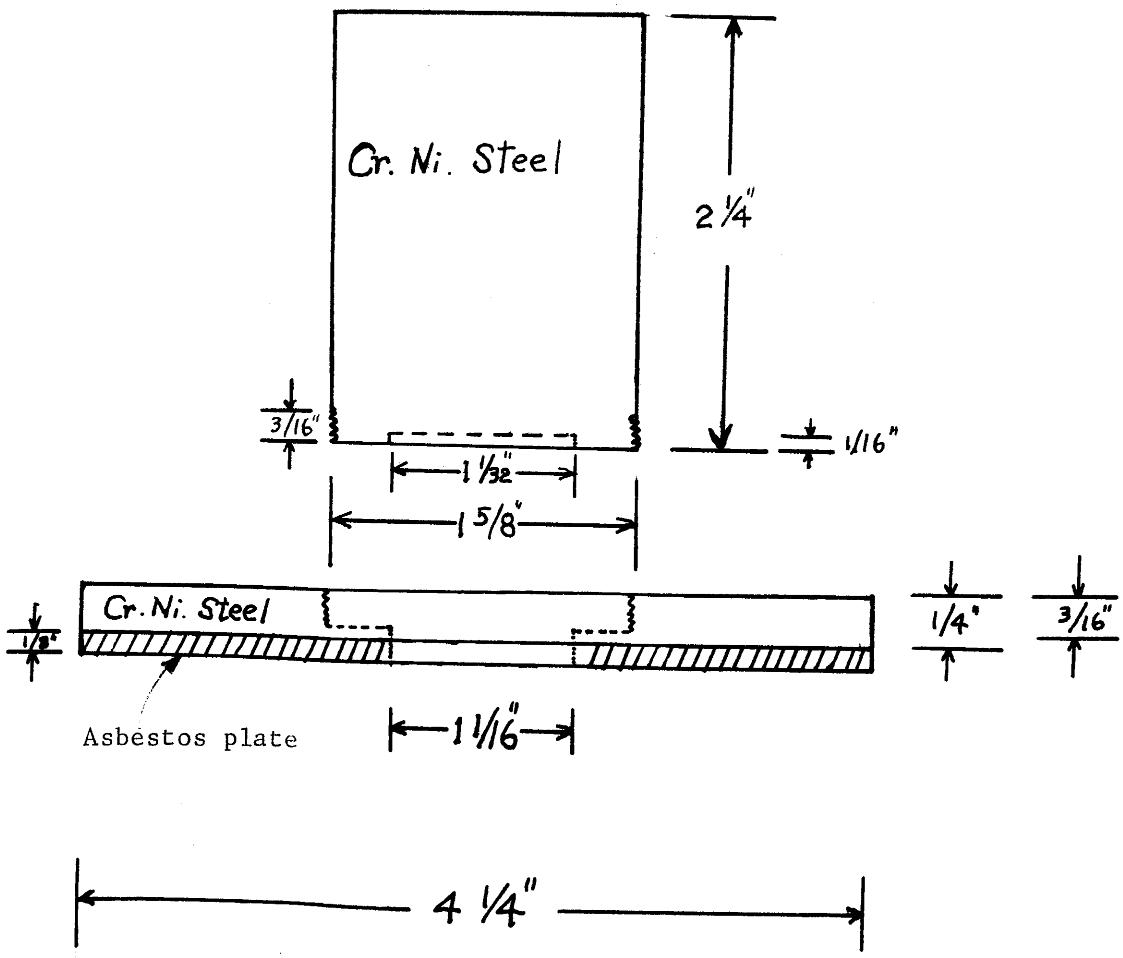


Fig. 12 Heater

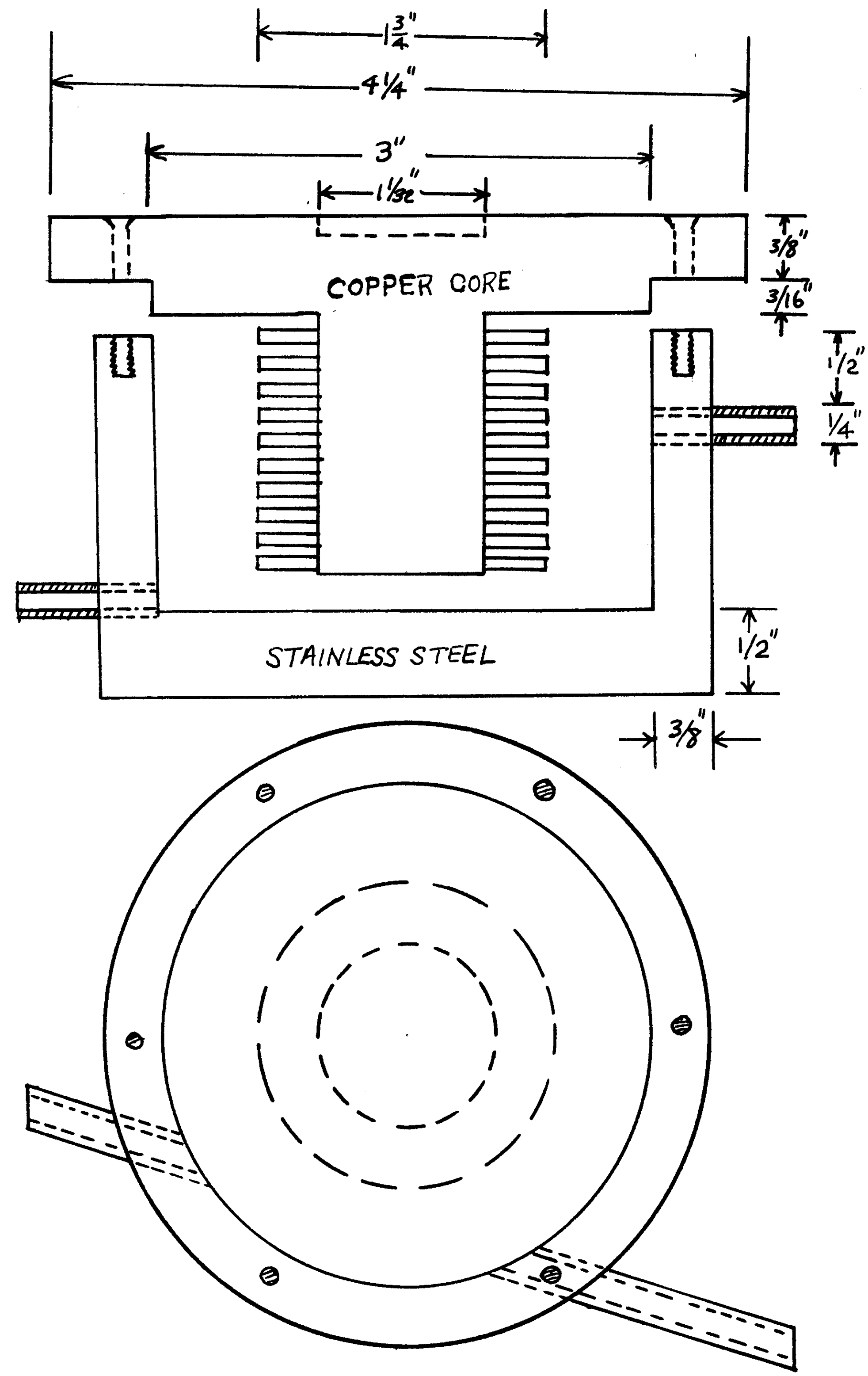


Fig. 13 Cooler sketch

Fig. 14 Al-Cr Thermocouple curve

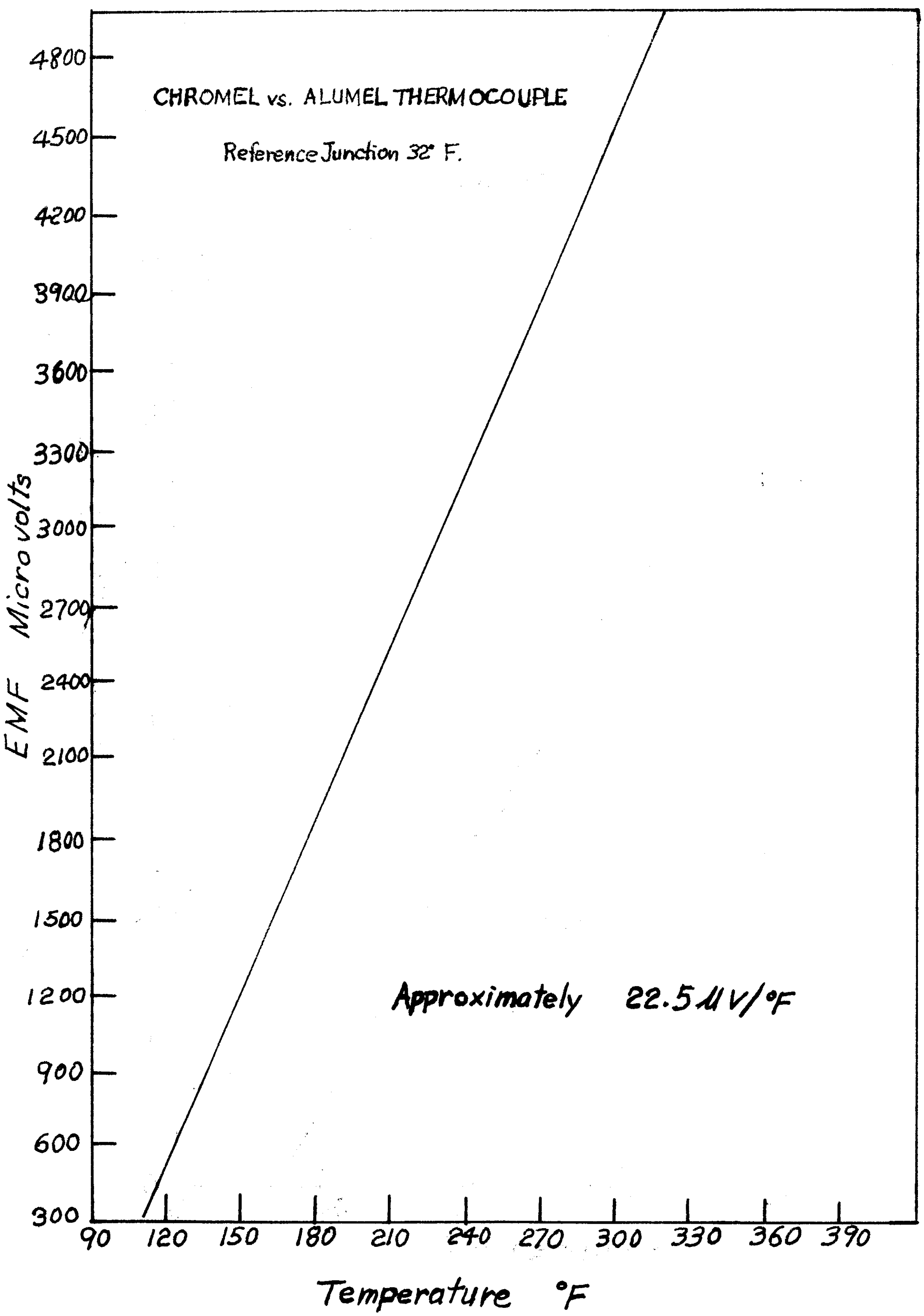
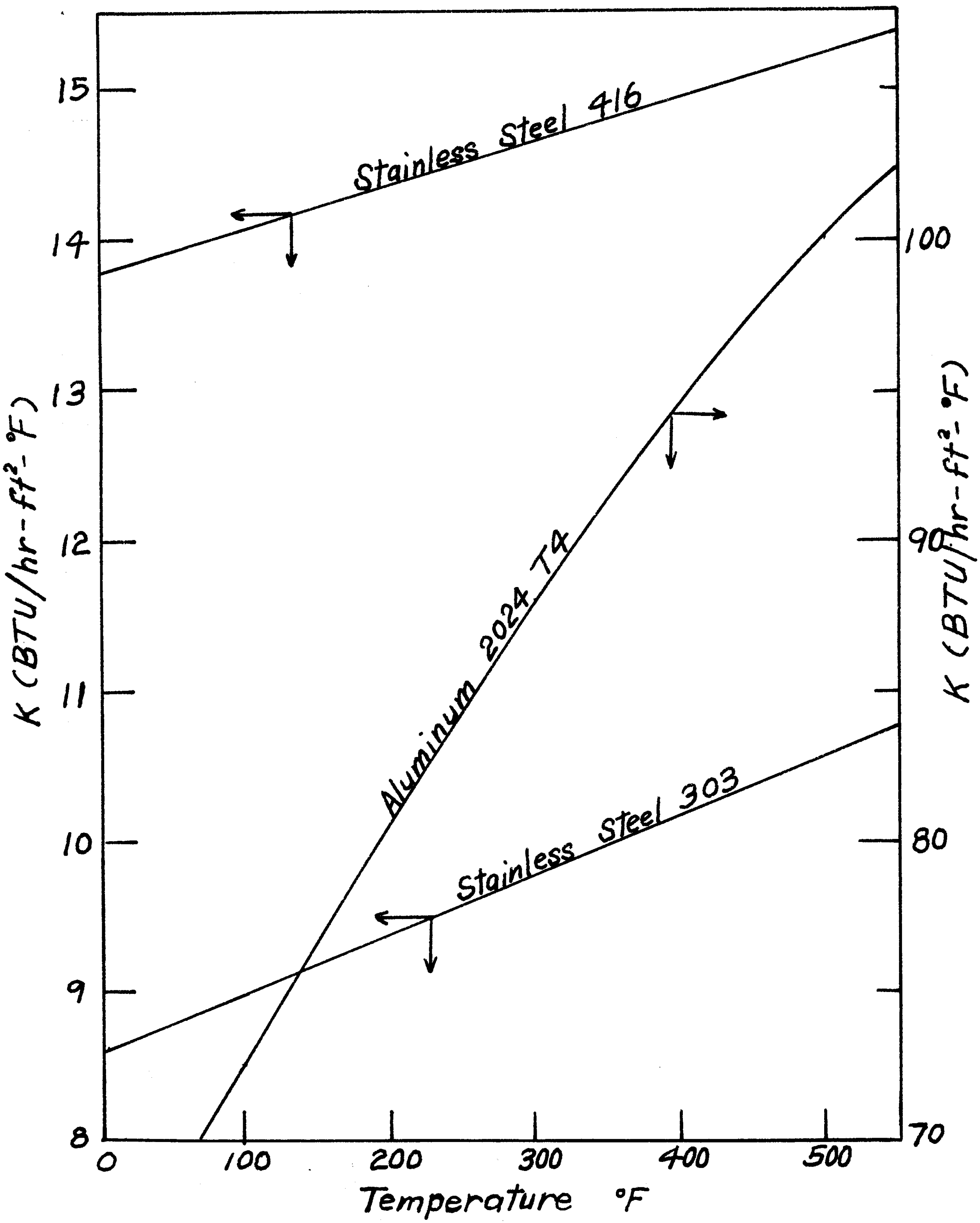


Fig. 15 Conductivity Curves



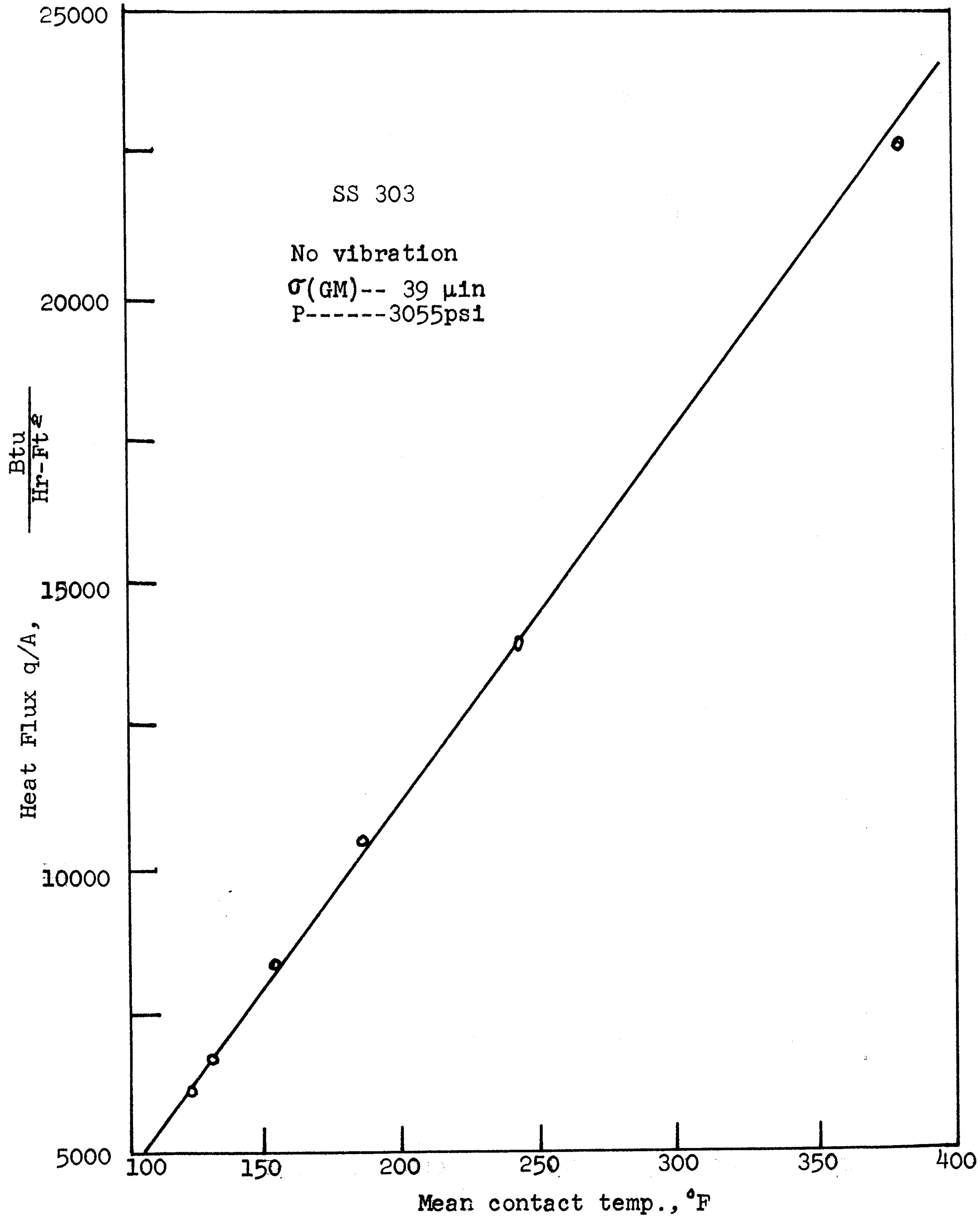

SS 303
No vibration
σ(GM)-- 39 μin
P-------3055psi
Heat Flux q/A, Btu/Hr-Ft²
Mean contact temp., °F
25000
20000
15000
10000
5000
100
150
200
250
300
350
400

Fig. 16

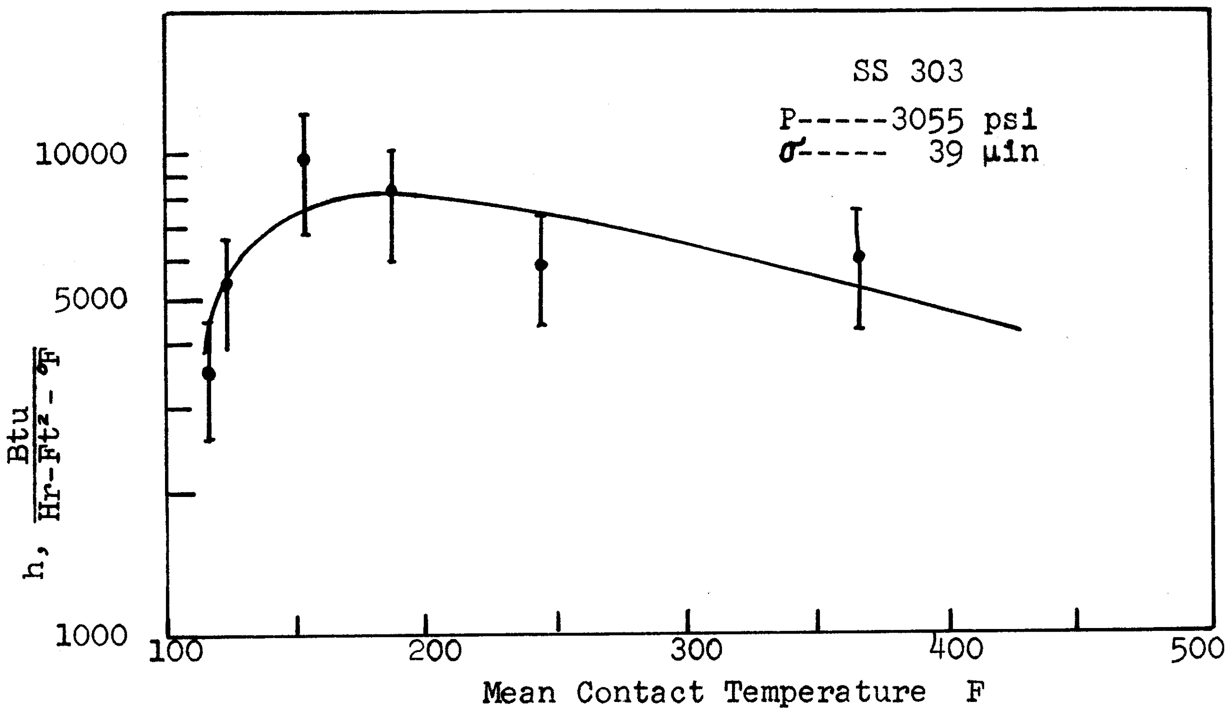

SS 303
P-----3055 psi
σ----- 39 μin
10000
5000
1000
h, Btu / Hr-Ft² - °F
100
200
300
400
500
Mean Contact Temperature F

Fig. 17

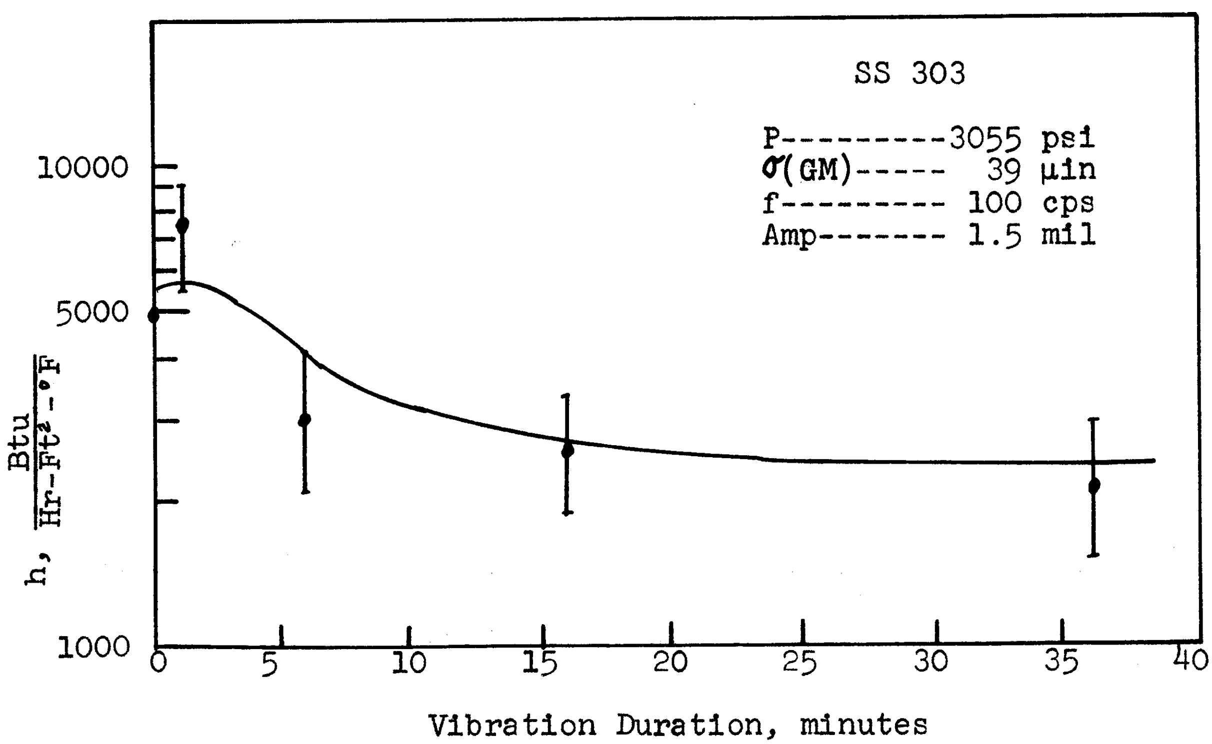
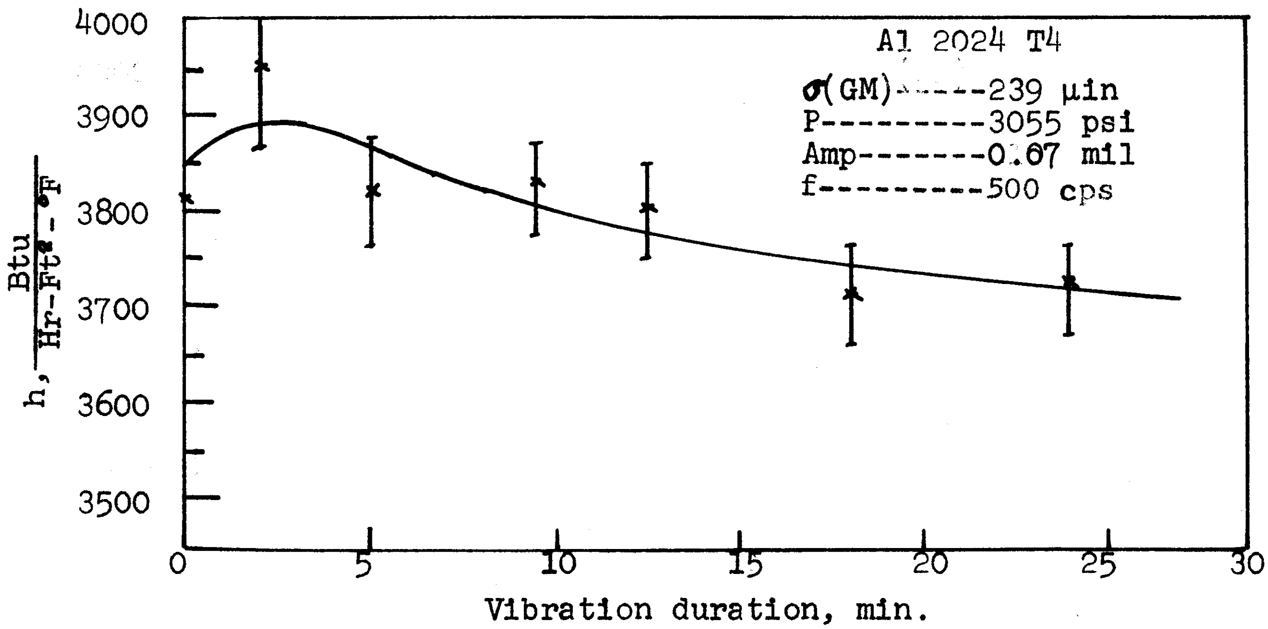
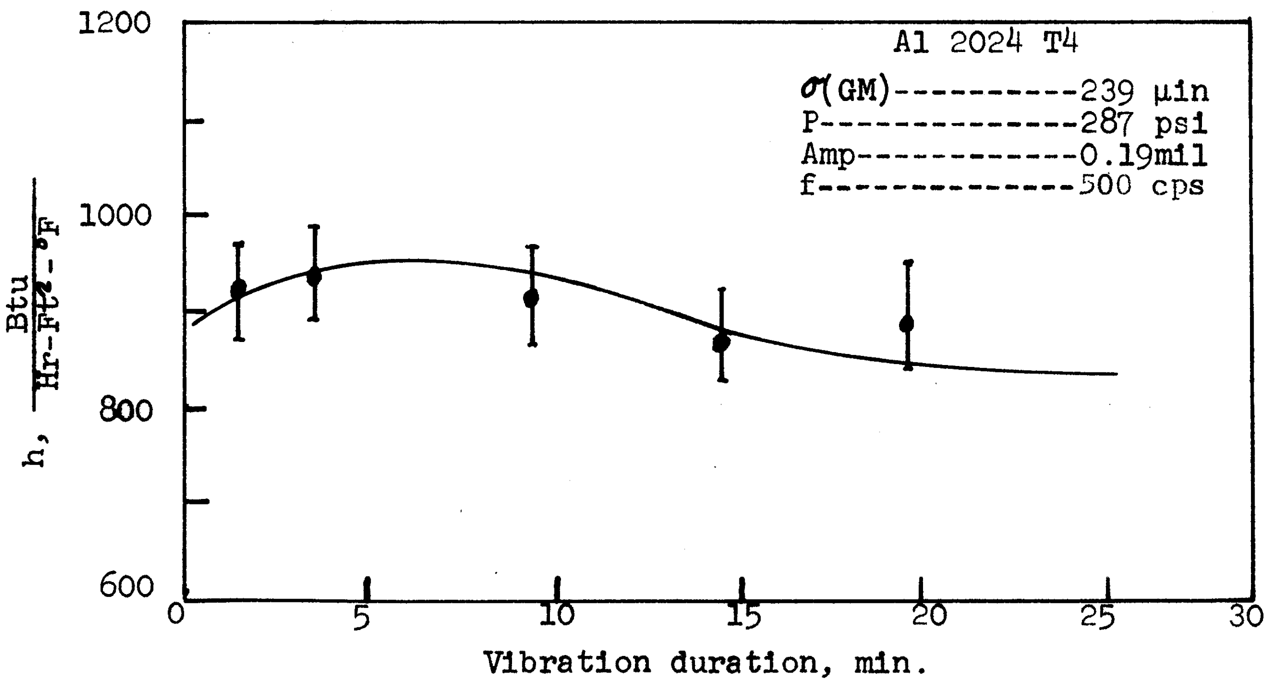

SS 303
P---------3055 psi
σ(GM)----- 39 μin
f--------- 100 cps
Amp------- 1.5 mil
10000
5000
1000
h, Btu / Hr-Ft² - °F
0
5
10
15
20
25
30
35
40
Vibration Duration, minutes

Fig. 18



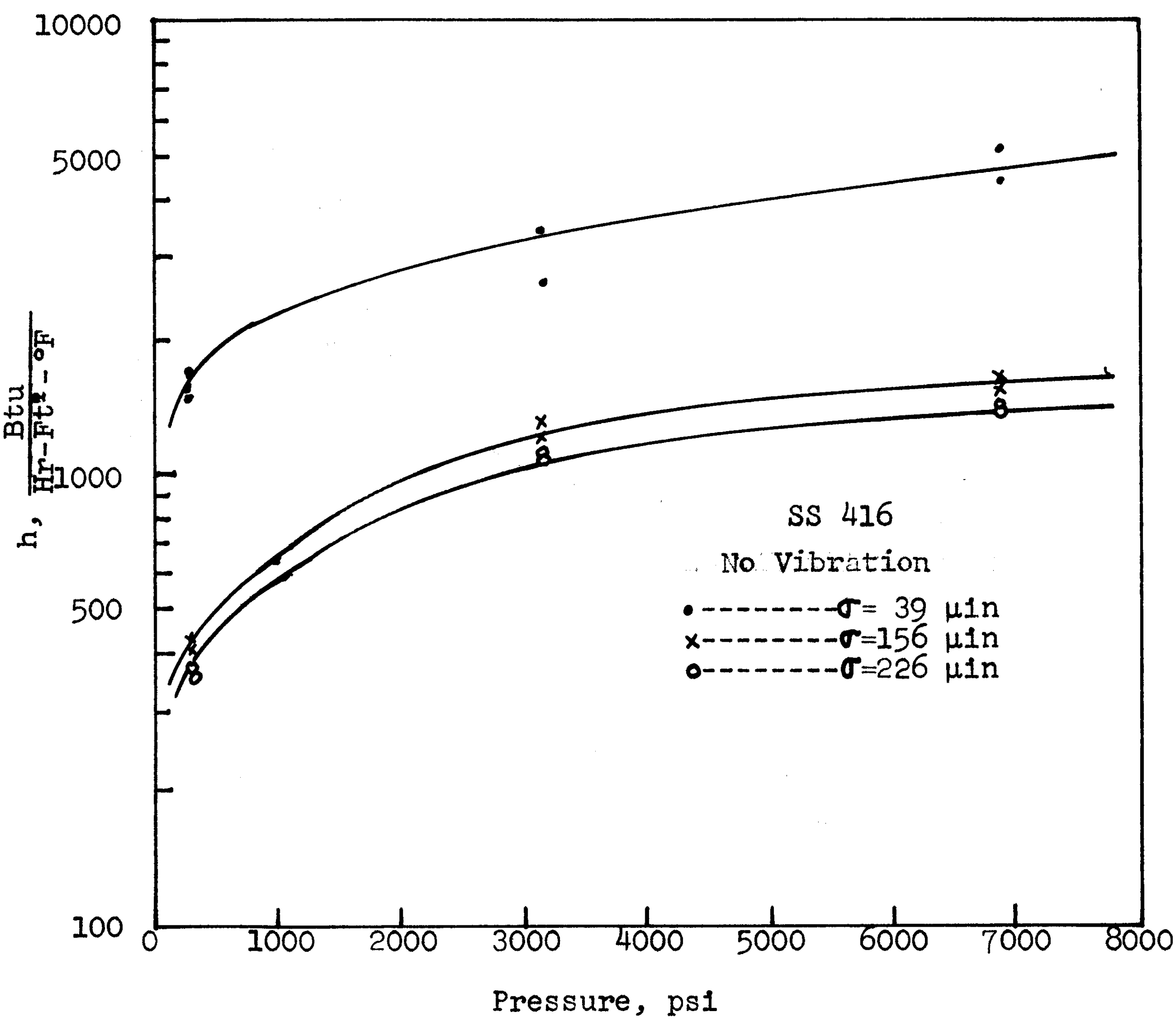
Al 2024 T4
σ(GM)------239 μin
P---------3055 psi
Amp-------0.67 mil
f---------500 cps
4000
3900
3800
3700
3600
3500
h, Btu / Hr-Ft²-°F
0
5
10
15
20
25
30
Vibration duration, min.

Fig. 19



Al 2024 T4
σ(GM)----------239 μin
P--------------287 psi
Amp------------0.19mil
f--------------500 cps
1200
1000
800
600
h, Btu / Hr-Ft²-°F
0
5
10
15
20
25
30
Vibration duration, min.

Fig. 20



10000
5000
1000
500
100
0
1000
2000
3000
4000
5000
6000
7000
8000
h, Btu / Hr-Ft² - °F
Pressure, psi
SS 416
No Vibration
• ---------σ= 39 μin
× ---------σ=156 μin
o ---------σ=226 μin

Fig. 21

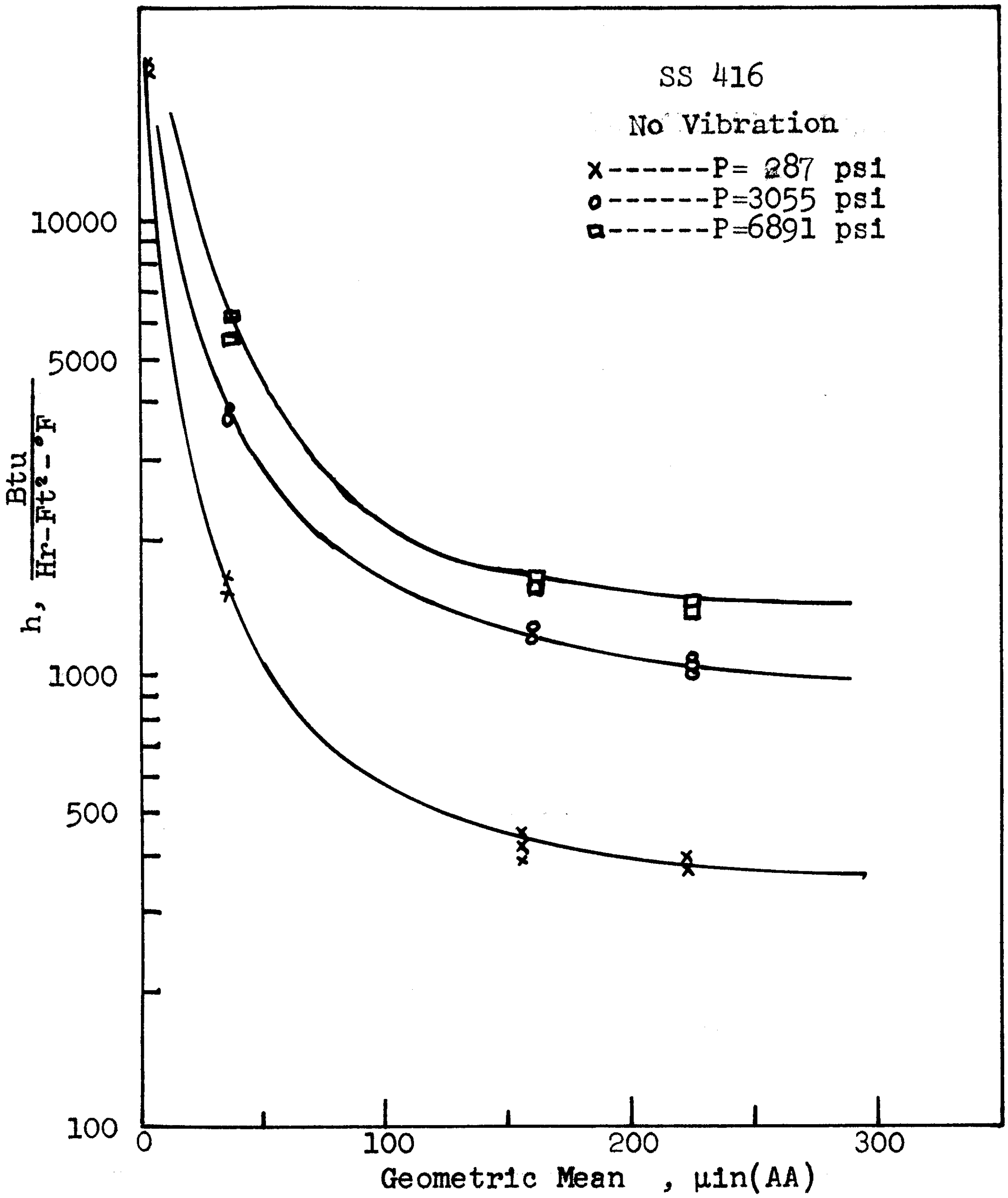

SS 416
No Vibration
x-------P= 287 psi
o-------P=3055 psi
□-------P=6891 psi
10000
5000
1000
500
100
h, $\frac{\text{Btu}}{\text{Hr-Ft}^2\text{-}^\circ\text{F}}$
0
100
200
300
Geometric Mean , μin(AA)

Fig. 22

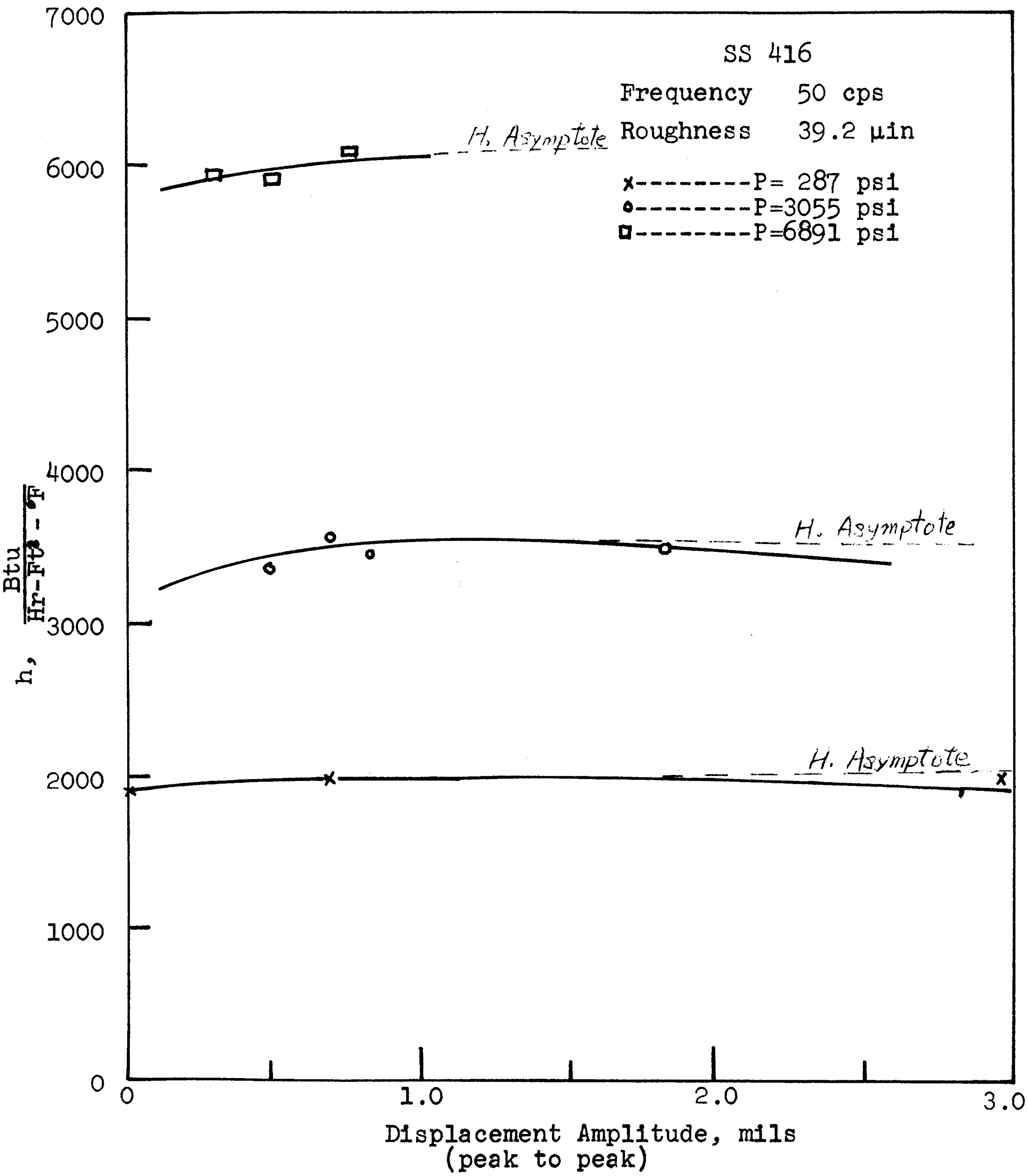
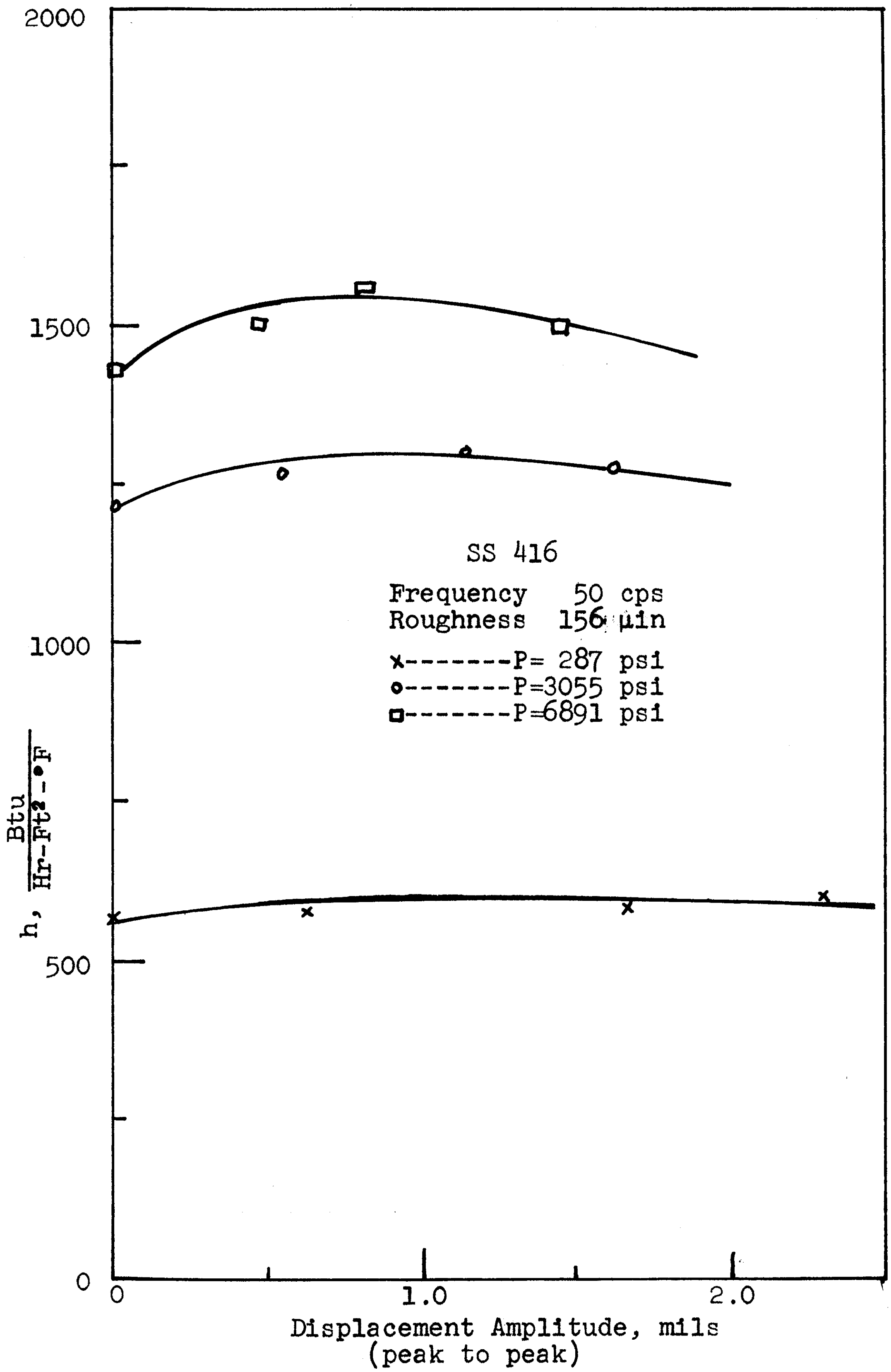
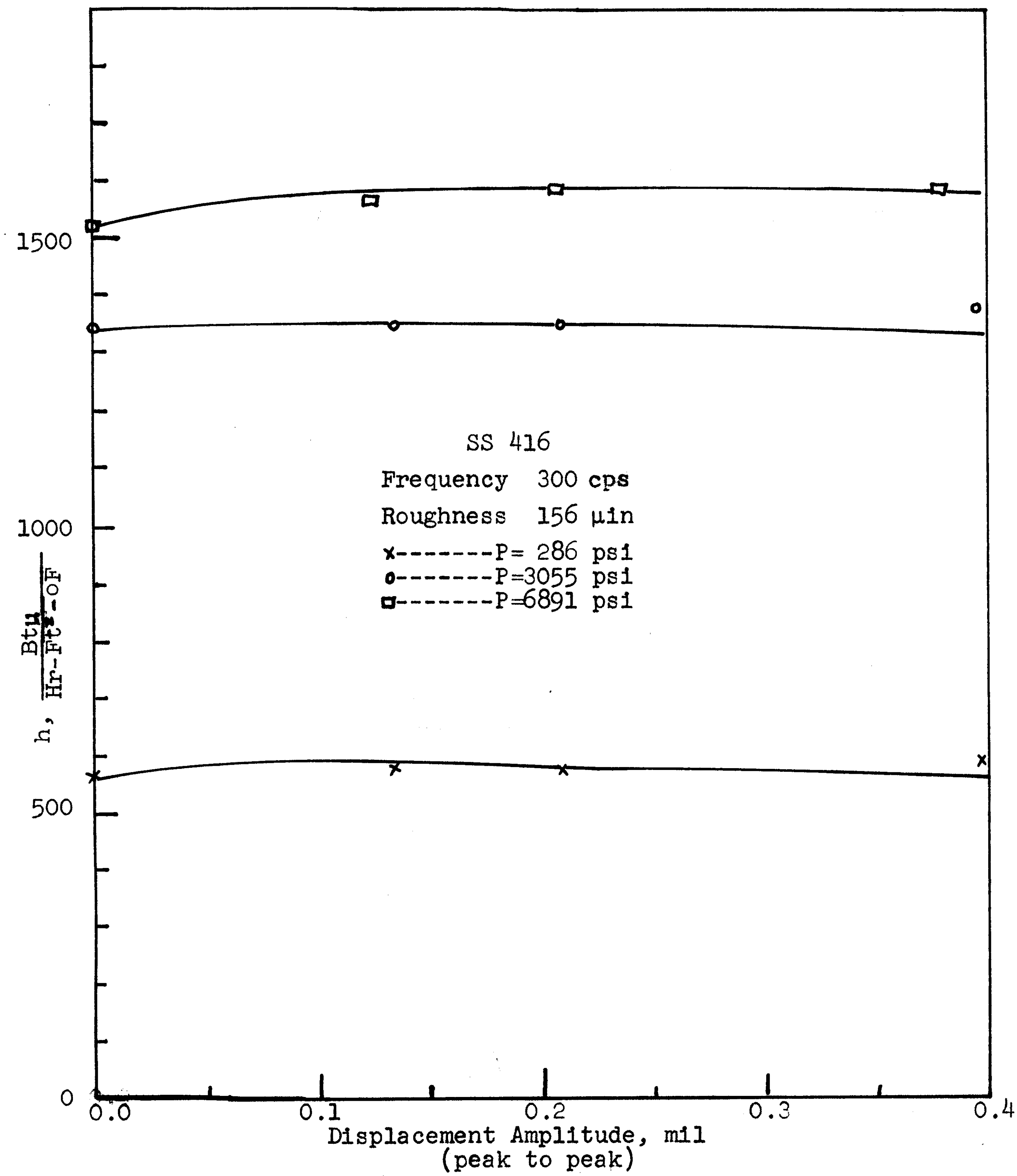

SS 416
Frequency 50 cps
Roughness 39.2 µin
P= 287 psi
P=3055 psi
P=6891 psi
H. Asymptote
H. Asymptote
H. Asymptote
h, Btu / Hr-Ft² - °F
7000
6000
5000
4000
3000
2000
1000
0
0
1.0
2.0
3.0
Displacement Amplitude, mils
(peak to peak)

Fig. 23



2000
1500
1000
500
0
h, $\frac{\text{Btu}}{\text{Hr-Ft}^2\text{-°F}}$
SS 416
Frequency 50 cps
Roughness 156 µin
x--------P= 287 psi
o--------P=3055 psi
□--------P=6891 psi
0
1.0
2.0
Displacement Amplitude, mils
(peak to peak)

Fig. 24



SS 416
Frequency 300 cps
Roughness 156 µin
x--------P= 286 psi
o--------P=3055 psi
□--------P=6891 psi
1500
1000
500
0
h, Btu / Hr-Ft²-°F
0.0
0.1
0.2
0.3
0.4
Displacement Amplitude, mil
(peak to peak)

Fig.25

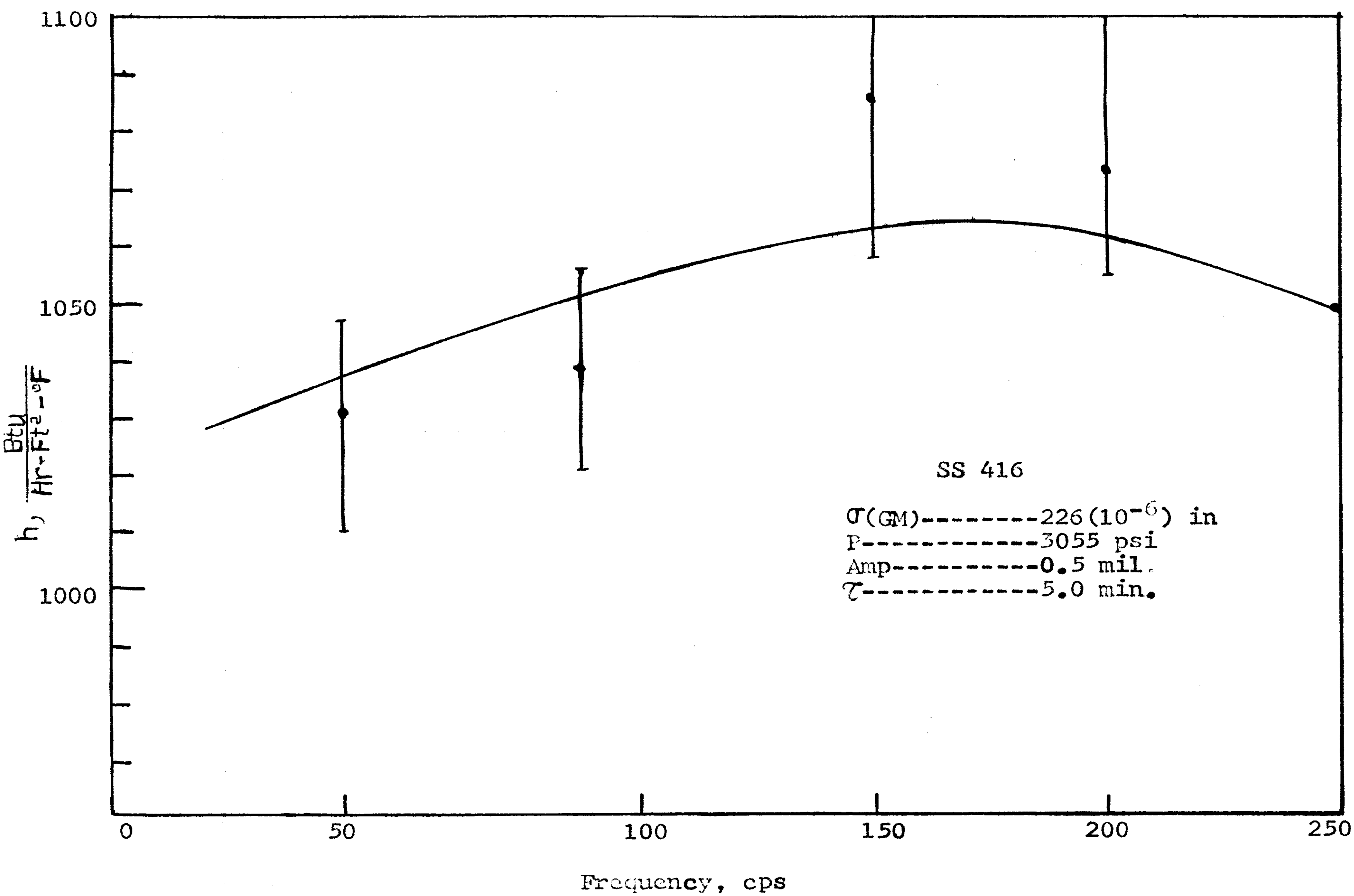

1100
1050
1000
$h, \frac{Btu}{Hr\text{-}Ft^2\text{-}°F}$
0
50
100
150
200
250
Frequency, cps
SS 416
σ(GM)---------226(10^{-6}) in
P------------3055 psi
Amp----------0.5 mil.
τ------------5.0 min.

Fig. 26

Al 2024-T4

σ(GM)------------239(10^{-6}) in
P---------------3055 psi
Amp-------------0.07 mil
τ---------------5.0 min. *

* Horizontal scale of Fig. 19 has been changed from Vibration duration to Vibration frequency (on 5.0 minutes vibration duration basis).

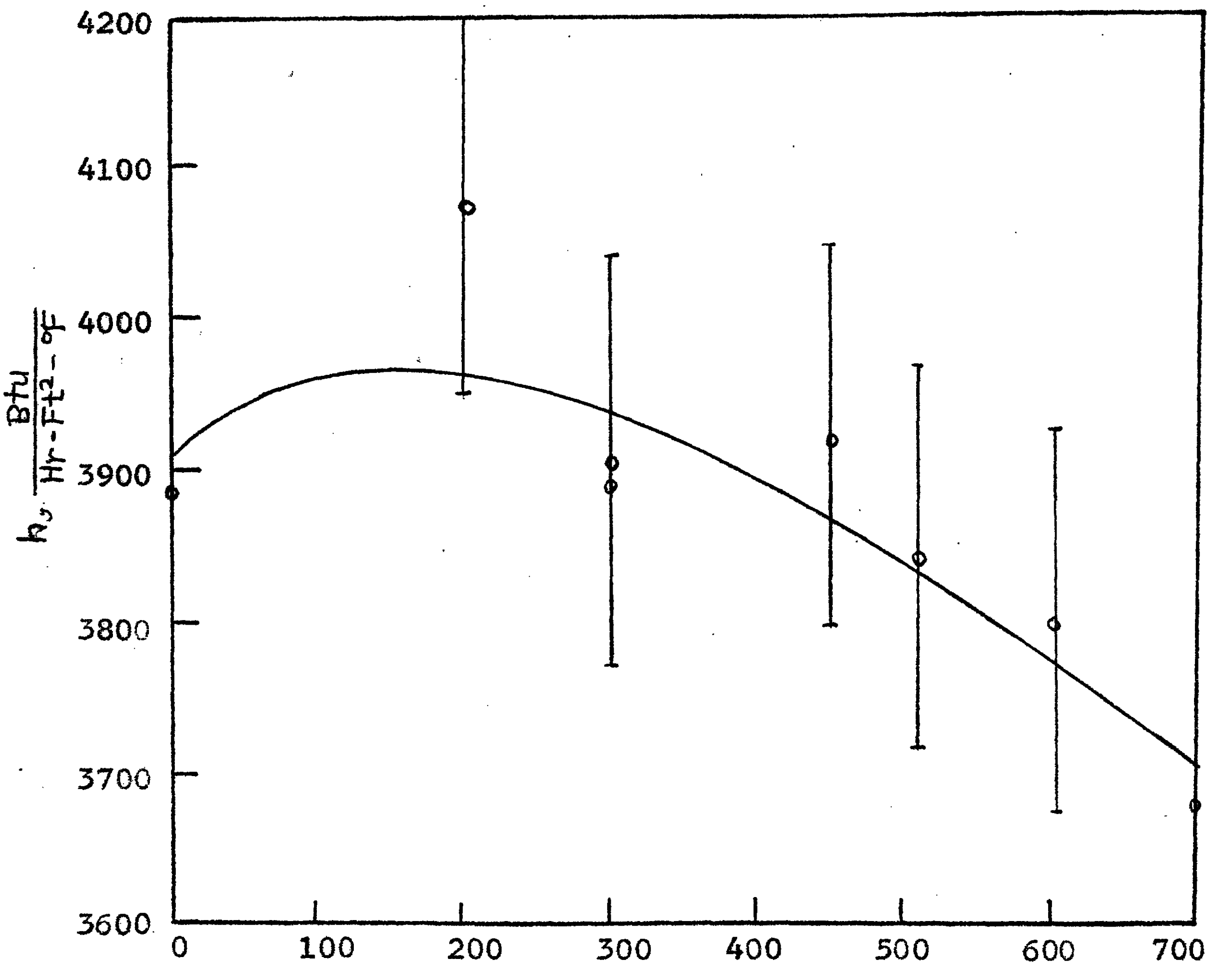


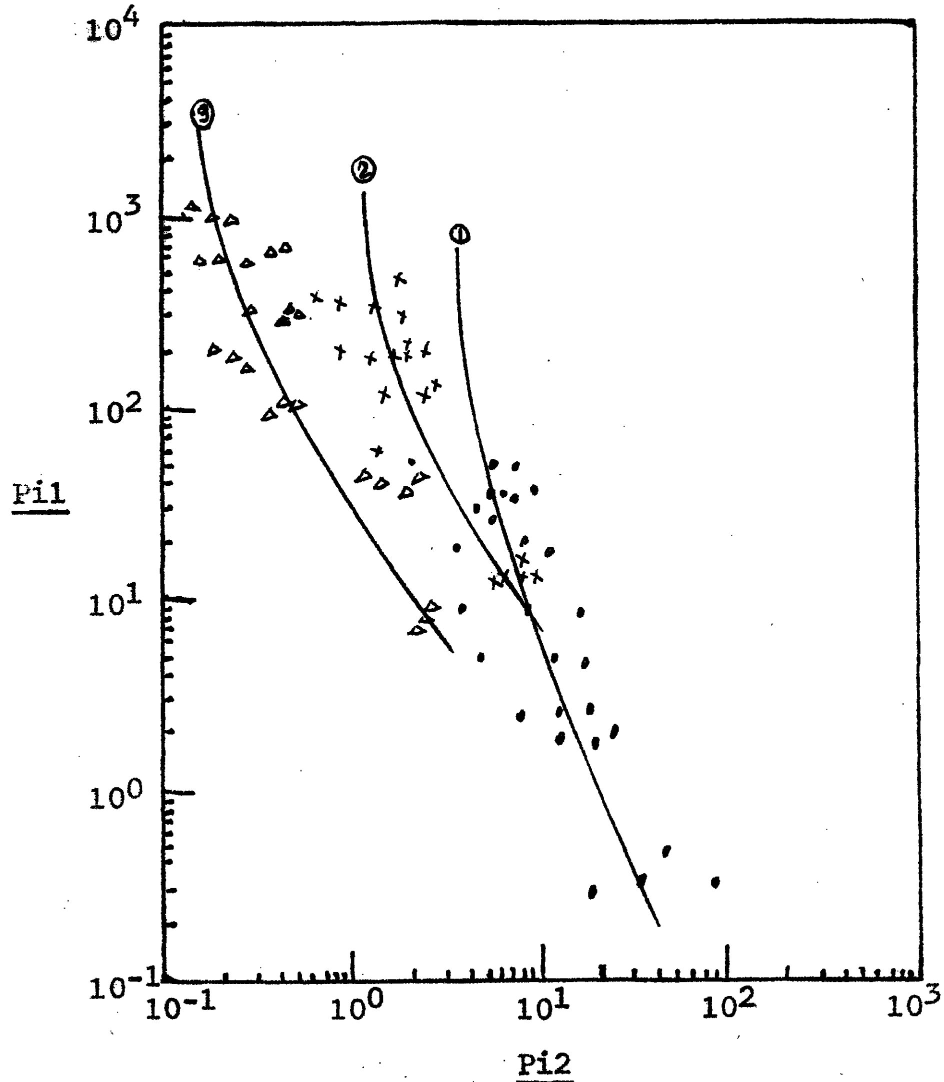
Fig. 27

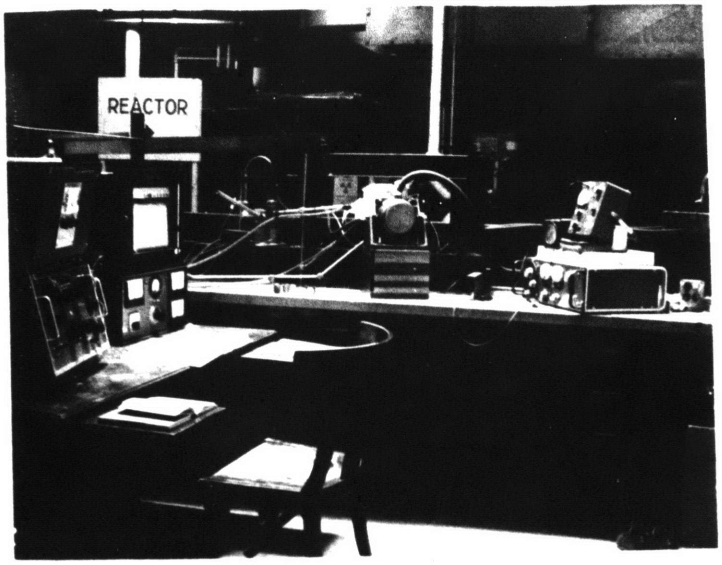
Fig. 28 Dimensional Analysis Result

$$\frac{\sigma P f}{T_0 h} = \Phi\left(\frac{A_{mp}}{\sigma}, f\tau\right)$$

$$Pi1 = \Phi\,(Pi2\ ,\ Pi3)$$

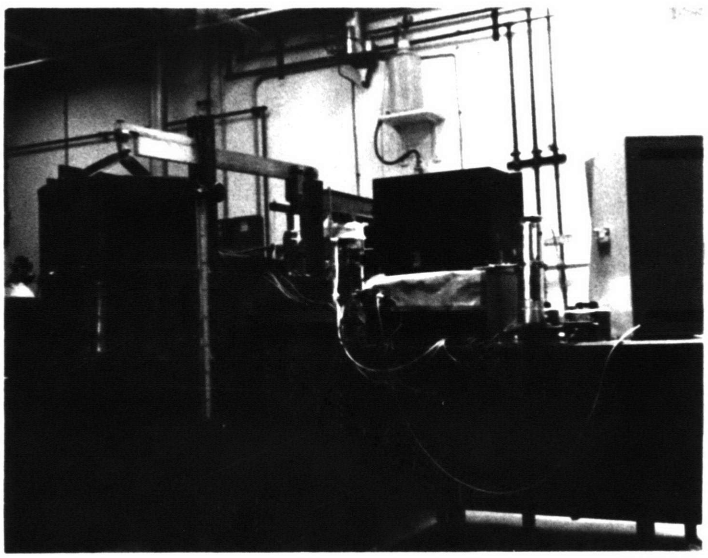
① -----Pi3=0.15(10^5)
② -----Pi3=0.90(10^5)
③ -----Pi3=0.30(10^6)





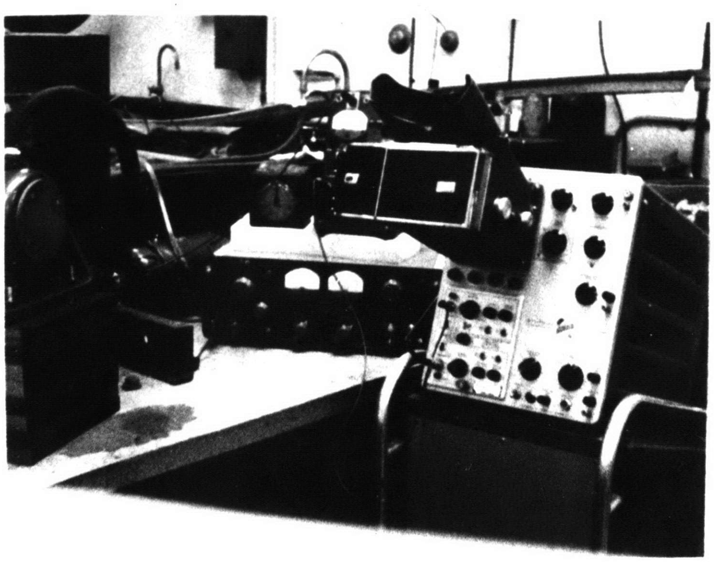
1.1

Front view of meter panel,potentiometer, recorder, vibrator, vibration meter and power amplifier. The test section is behind the vibrator.



1.2

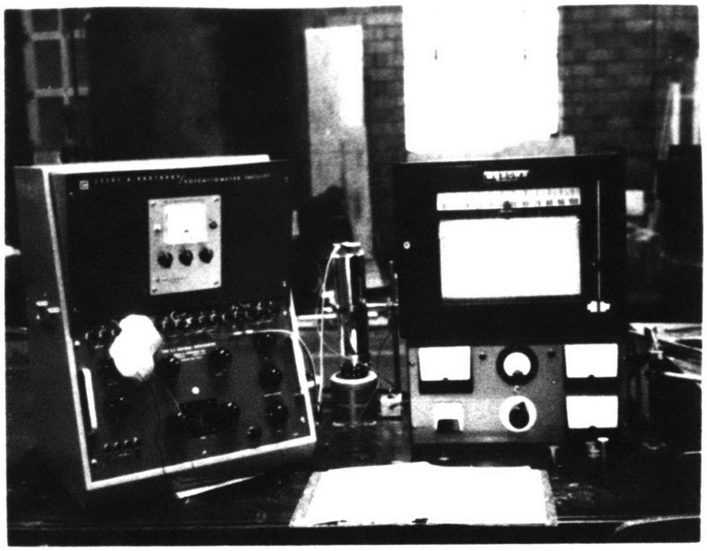
Side view of the press. The gasoline tank is a dead weight for the press. It weighs one hundred and fifteen lbs.



1.3

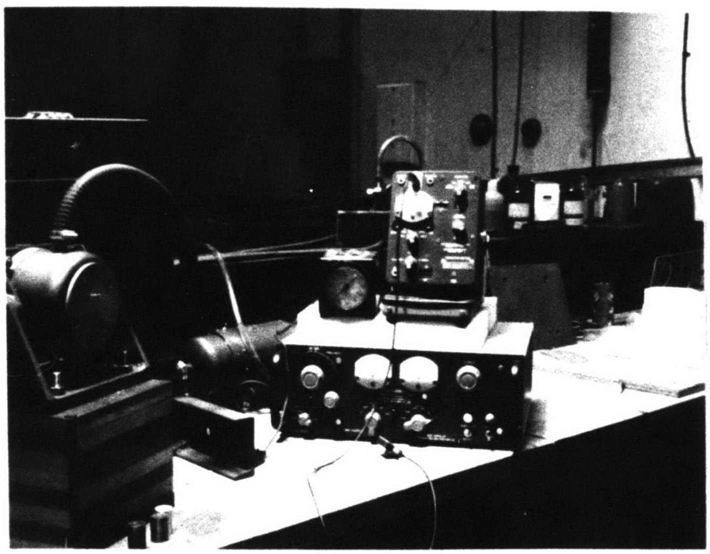
Setup for taking pictures of vibration waveforms. The output of the vibration meter is fed into the scope.

plate 1 Pictures of instruments I



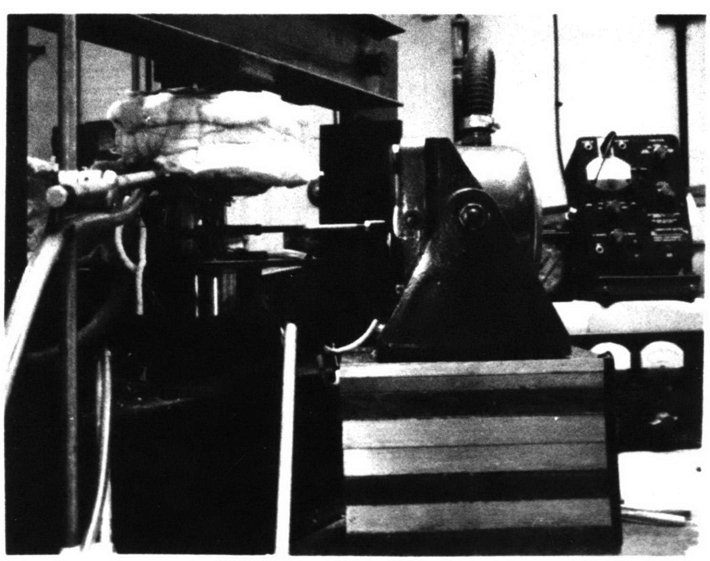
2.1

Close-up view of the LN potentiometer, the Brown Recorder and meter panel.



2.2

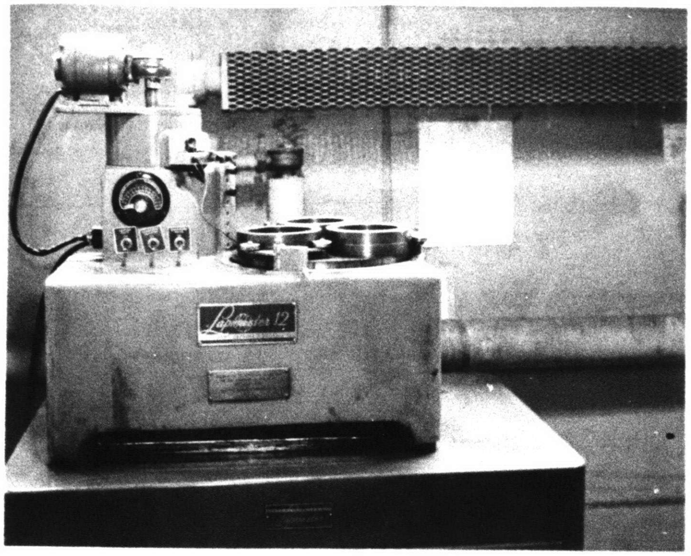
Close-up view of the GR vibration meter and GR power amplifier. The vibration pickup is shown in front of the power amplifier.



2.3

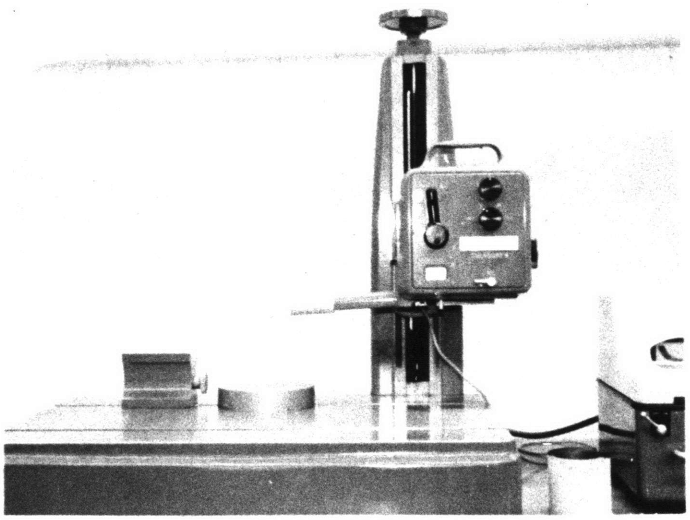
Close-up view of Goodmans V-50 vibrator and the coupler connected to the test specimen. The hose on top of the vibrator is for air-cooling.

Plate 2 Pictures of instruments II



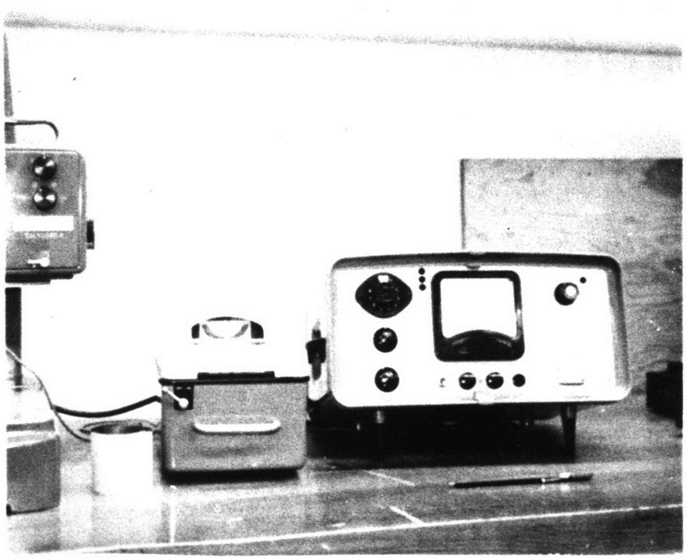
3.1

Lapmaster for surface flatenning of the test specimens.



3.2

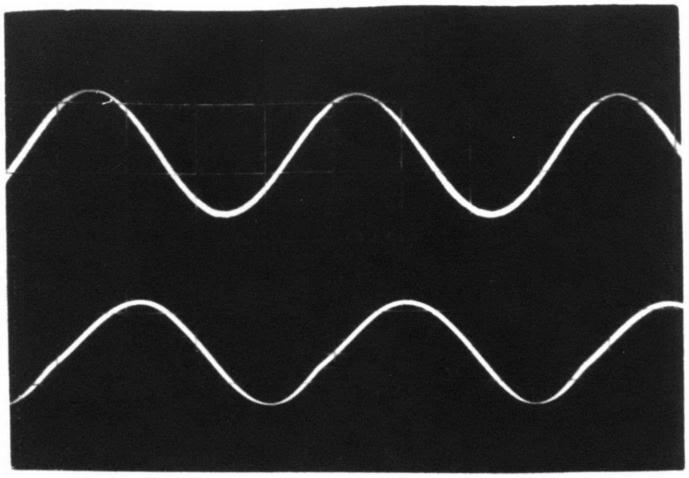
Mechanical section of the surface analyzer, TALYSURF 4.
A diamond needle is attached at the end of the horizontal bar.



3.3

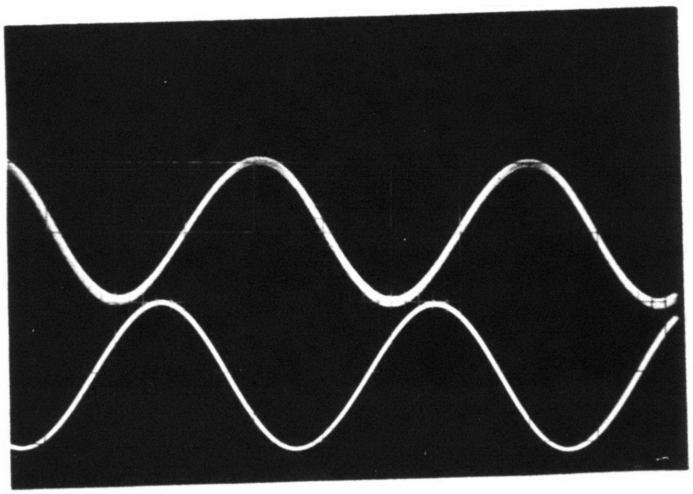
Electrical section of the surface analyzer. Recorder is on the left, amplifier with meter display is on the right.

Plate 3 Pictures of surface preparation equipments



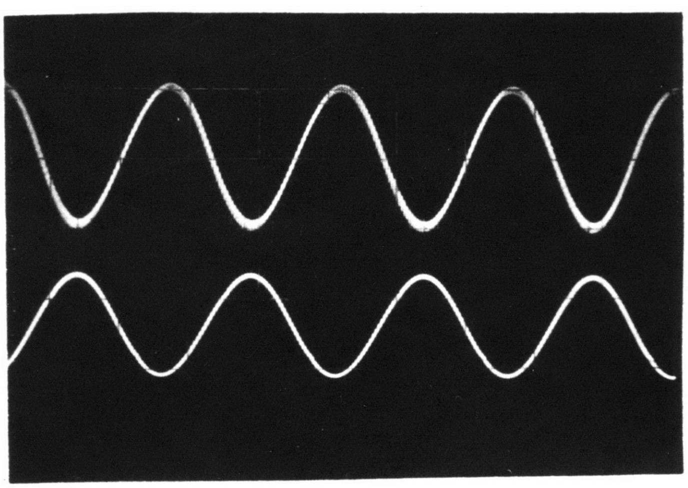
4.1

Displacement output
waveform at no-load.
Horizontal sensitivity
5 ms/cm
Input frequency 50 cps



4.2

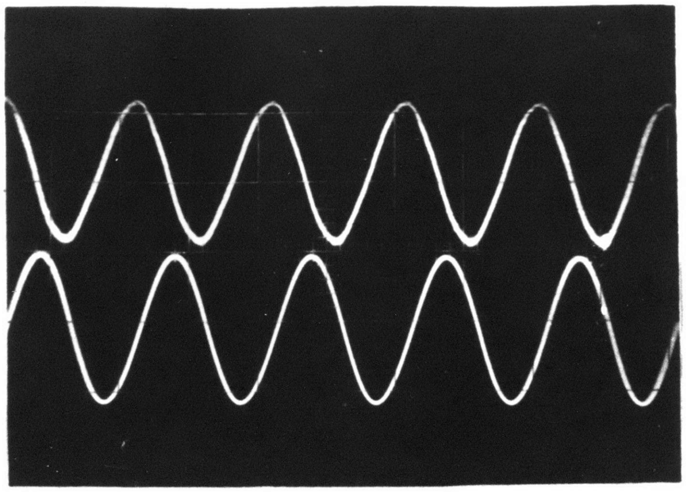
Displacement output
waveform at no-load.
Horizontal sensitivity
0.5 ms/cm
Input frequency 500 cps



4.3

Displacement output
waveform at no-load.
Horizontal sensitivity
0.2 ms/cm
Input frequency 2000 cps

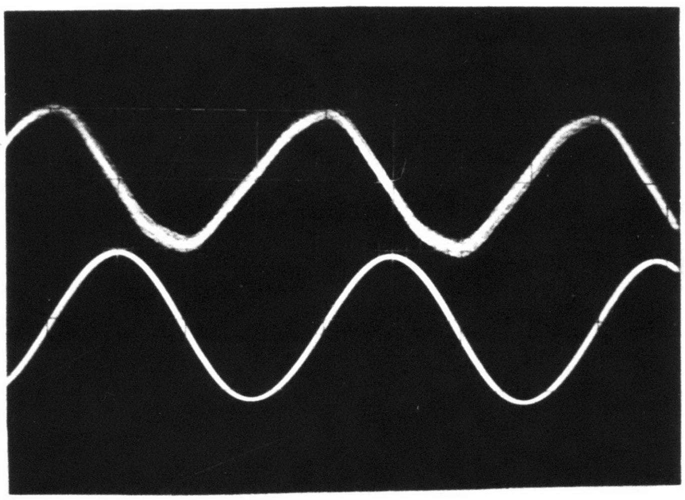
Plate 4 Vibration output waveforms(upper) and
its electrical signal waveforms(lower)



5.1

Acceleration output
waveform at no-load.

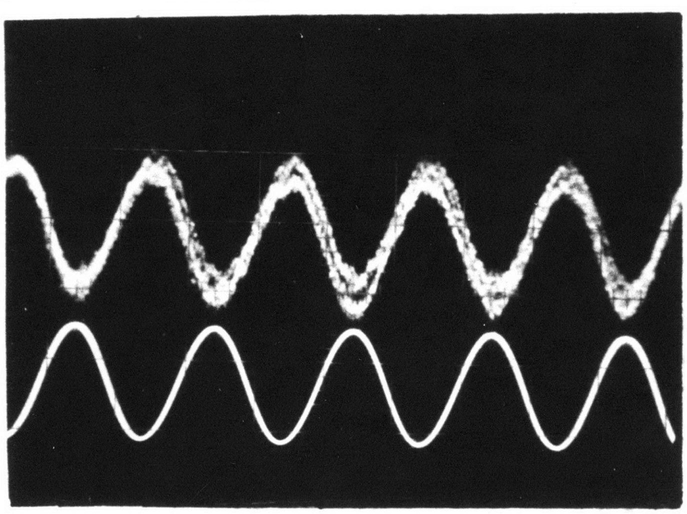
Horizontal sensitivity
1.0 ms/cm
Input frequency 500 cps



5.2

Velocity output output
waveform at no-load.

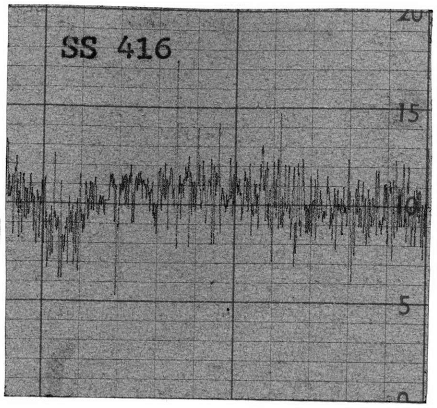
Horizontal sensitivity
0.5 ms/cm
Input frequency 500 cps



5.3

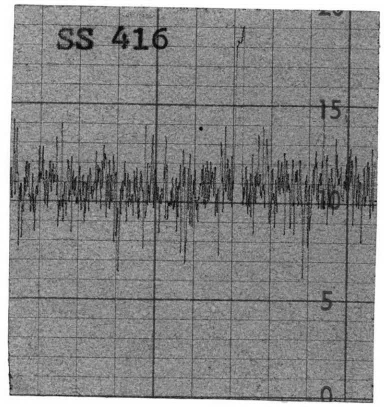
Displacement output
waveform in actual
test.
Horizontal sensitivity
0.2 ms/cm
Input frequency 210 cps

Plate 5 Vibration output waveforms(upper) and
its electrical signal waveforms(lower)



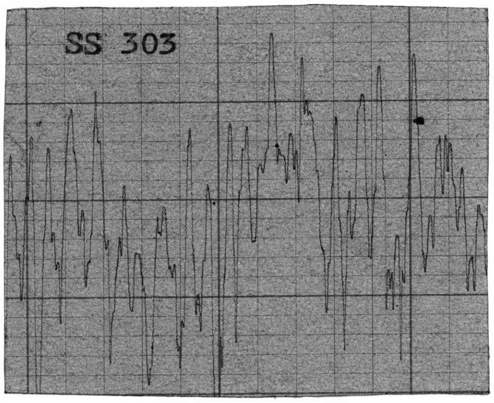
Magnified by 20,000

Roughness 6.5(10^{-6})in.



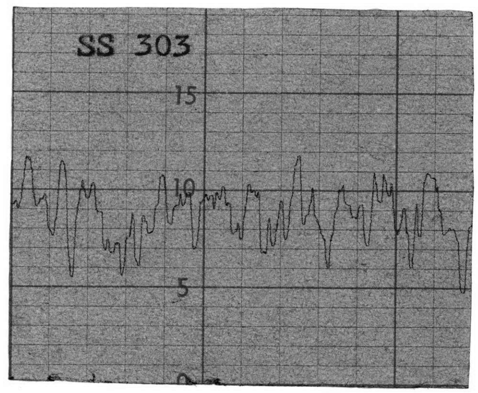
Magnified by 20,000

Roughness 6.9(10^{-6})in.



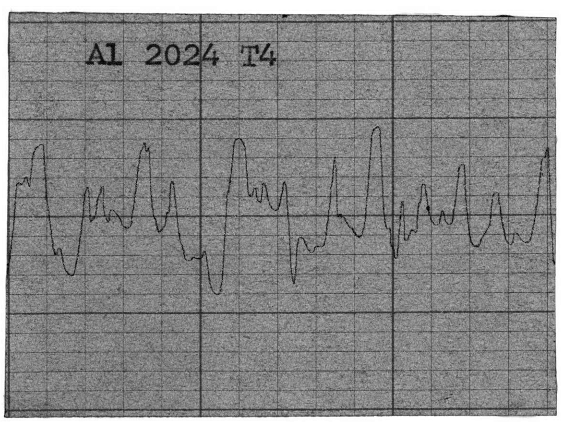
Magnified by 5,000

Roughness 28.3(10^{-6})in.



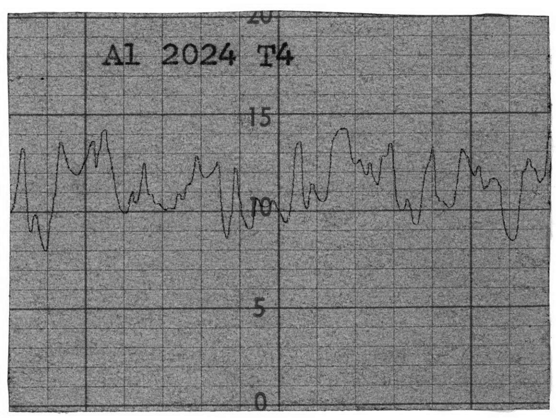
Magnified by 2,000

Roughness 53.7(10^{-6})in.



Magnified by 500

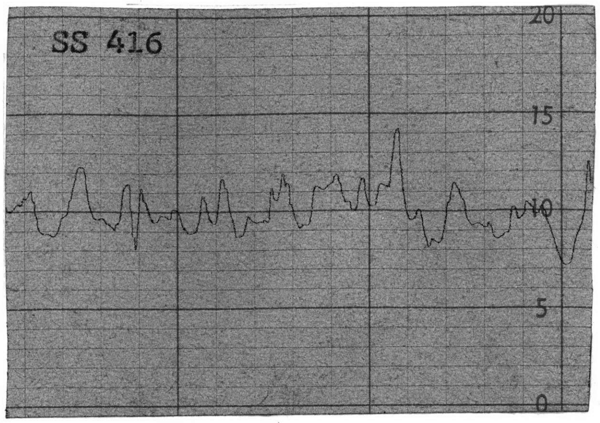
Roughness 281(10^{-6})in.



Magnified by 500

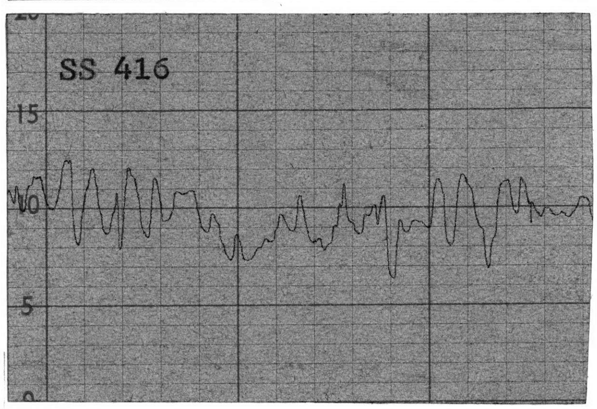
Roughness 202(10^{-6})in.

Plate 6, Surface Profiles I



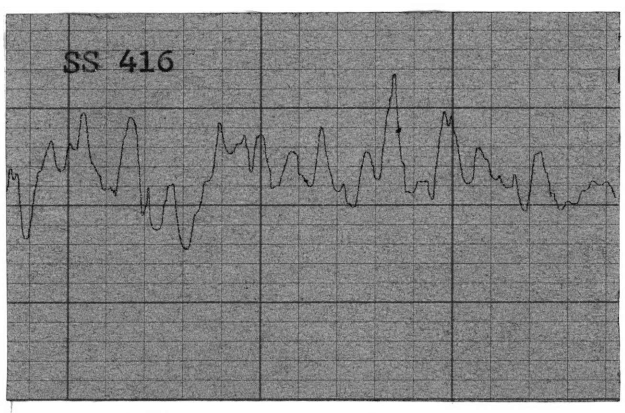
Magnified by 500

Roughness $153(10^{-6})$in.



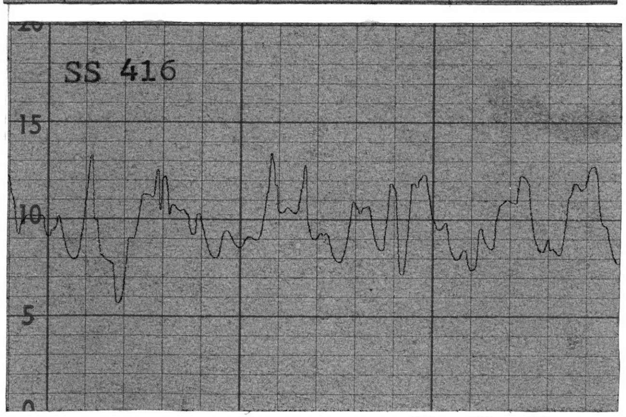
Magnified by 500

Roughness $156(10^{-6})$in.



Magnified by 500

Roughness $217(10^{-6})$in.



Magnified by 500

Roughness $235(10^{-6})$in.

Plate 7, Surface Profiles II

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